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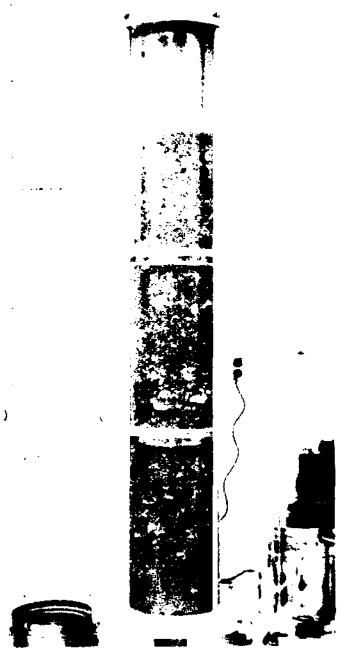

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COMPACTION CHARACTERISTICS OF EARTH-ROCK MIXTURES

by

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This report presents the results of a major laboratory research investigation into the compaction characteristics of gravelly soils, i.e., earth-rock mixtures. Test gradations were based on successive scalping, had maximum particle sizes up to the 3-in. US Standard Sieve size, and contained both clay (CH) and silt (ML) fines. Laboratory compaction test procedures employing 6-, 12-, and 18-in. diameter molds with a mechanical compactor were developed and shown to be acceptably free of mold size effects. Those procedures were used to perform standard effort compaction tests on the test gradations. Analyses of the data include treatment of the effects of scalping, plasticity of fines, and gravel content on the maximum dry unit weight and optimum water content. Current methods for correcting the compaction parameters obtained on a fraction to predict those of the total material are examined. A new fill compaction control method is developed which is based on either the minus 3/4-in. or minus No.4 fraction, is more accurate than existing methods, and offers the advantage of avoidance of large-scale testing of the total materials.

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PREFACE

This investigation is part of a study to improve understanding of the engineering properties and behavior of soils containing large particles and to develop laboratory testing procedures which more accurately measure or predict those properties and behavior than methods currently in use. Funding for the work is provided by the Headquarters, US Army Corps of Engineers (USACE) under the Civil Works Research and Development Program (CWRD) work unit No. 32342, entitled "Testing Large-Particled Soils." The USACE Technical Monitor for this work unit is Mr. Richard F. Davidson, Directorate of Civil Works, Engineering Division, Geotechnical and Materials Branch, Soils Section, USACE, Washington, DC. The Program Manager is Mr. G. P. Hale, Chief, Soils Research Center (SRC), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS.

The Principal Investigator for CWRD work unit No. 32342 is Dr. Victor H. Torrey III, of the Soil Mechanics Branch (SMB), S&RMD, GL, WES. The laboratory testing was under the direct supervision of Mr. Robert T. Donaghe assisted by Mr. Charles E. Carter both of the Soils Research Facility, SRC, S&RMD. This report covers research conducted during the period January 1982 to January 1989 and was prepared by Dr. Torrey and Mr. Donaghe under the general supervision of Messrs. C.L. McAnear and G.P. Hale, former Chief and Acting Chief, respectively, Soil Mechanics Division, Dr. Don C. Banks, Chief, S&RMD, and Dr. William F. Marcuson III, Chief, GL.

Coordination of preparation of this report for publication was performed by Mrs. Joyce Walker of the WES Visual Production Center, Information Technology Laboratory.

COL Larry B. Fulton, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic inches	16.38706	cubic centimetres
feet	0.3048	metres
foot-pounds (force)	1.355818	metre-newtons or joules
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square inches	6.4516	square centimetres

COMPACTION CHARACTERISTICS OF EARTH-ROCK MIXTURES

PART I: INTRODUCTION

Background

1. Before addressing the subject of this report, it is appropriate to place the reference to earth-rock mixtures in perspective as is necessary to establish a distinction between such materials and those termed as "rockfill". Fortunately, at least within the experience of the Corps of Engineers (USACE), this is a practical undertaking because review of earth and/or rockfill dam projects permits a general, although not precise, distinction. The authors recognize the variations in those project records which in some cases may contradict some aspects of the following definitions. Nonetheless, for the purposes of this report, earth-rock mixtures are coarse-grained,(less than 50 percent passing the U.S. Standard No. 200 sieve), gravel or gravelly, cohesive and cohesionless materials. In addition, these materials are "designed" as compacted fill by assessment of their properties through laboratory testing to establish fill compaction specifications. These specifications take the form of placement water content and density if sufficient fines are present or for relative density if the soil is cohesionless. Furthermore, the compaction of these materials is controlled in the fill operation by regular comparison of field measurements of those parameters to the specified values or ranges in values. In contrast, rockfill is typically dealt with in a more qualitative than quantitative manner with placement and compaction procedures determined by means of test fills and test quarries (Hammer and Torrey 1973) to identify the most efficient quarrying, processing and handling operations, to select the most efficient combination of equipment versus loose lift thickness and to obtain (usually) a "free draining" compacted mass. During construction, the selected procedures for rockfill are ordinarily followed without regular attention to fill testing unless apparently adverse changes are noted in materials or compacted fill qualities. Rockfill is typically cohesionless and composed of larger particles (say, up to 24-in.) and compacted in much thicker lifts (say, up to 36-in.) than earth-rock mixtures which often contain plastic fines and are seen in the case histories to have been restricted to a maximum

particle size of about 6-in. (either naturally or by removal of particles in excess of that size) and compacted in lift thicknesses of less than 12-in.

2. Laboratory tests to obtain moisture-density relationships for soils containing large particles, i.e., earth-rock mixtures, have been both problematical and questionable over the years. The problem in dealing with such materials arises from the fact that if the full-scale gradation is to be tested, the size of the laboratory test specimen must be sufficiently large to assure assessment of the properties and/or behavior of the mixture. There seems to be general, although informal, agreement within the profession in this country that the ratio of test specimen diameter to largest particle size should be no lower than 5 or 6 to achieve a good test on the mixture. Both Corps of Engineers' (Engineer Manual, EM 1110-2-1906, "Laboratory Soils Testing" 1973) and American Society for Testing and Materials' (ASTM 1991 Annual Book of ASTM Standards, Section 4, Vol 04.08) methods conform to this concept. Working with a ratio of 5 or 6 leads to what would be conventionally considered large test specimens (in excess of 6-in. in diameter) when the largest particle size begins to exceed 1-in. Testing of larger specimens entails the need for larger and more expensive laboratory hardware, higher capacity compaction and/or loading mechanisms, special processing and handling equipment, more spacious facilities, specialized instrumentation, and lots of hard manual labor. Therefore, beginning years ago, as one laboratory after another began to encounter these realities in testing soils containing large particles, methods were developed or adopted on faith which were believed to provide adequate estimates of full-scale gradation properties but which also circumvented testing of large specimens of the full-scale materials. Simplistically, the avoidance procedures have included practices such as discarding the larger particles (scalping), or scalping and then replacing the "oversized" fraction with an equal portion by weight of manageable sizes, or even the creation of a "parallel" gradation with a smaller maximum particle size. Formal research to assess the reliability of methodologies for testing earth-rock mixtures has been very sporadic and has mostly fallen to organizations engaged in regular major design and construction activities involving these materials such as the USACE, U. S. Bureau of Reclamation (USBR) and some state agencies (including universities). However, because of the expense, time consuming nature of the work, and the many variables commensurate with earth-rock mixture research, sporadic efforts have not sufficed to eliminate many of the basic questions.

This fact is typified by the current realization in the profession that the long-standing and popular procedure of scalping with replacement to reduce maximum particle size and, thus, test specimen diameter, should not generally be assumed to yield test results satisfactorily indicative of full-scale gradation properties or behavior. This is not to say that there have been no materials encountered for which scalping/replacing was not adequate, but that this procedure should not be presumed as ordinarily adequate. Although not the subject of this report, it is pointed out that all of the above statements apply equally to the proposition of determining the strength and deformation properties of earth-rock mixtures by means of the triaxial test.

3. At present, the USACE practice (EM 1110-2-1906, Appendix VIA) in performing laboratory compaction tests on earth-rock mixtures containing sufficient fines to produce a well defined moisture-density curve entails a 12-in. diam mold and an 11.5 lb., hand-held rammer. The maximum mold size of 12-in. confines the test to a maximum particle size of 2-in. Plus 2-in. fractions constituting less than 10 percent by weight of the total material may be scalped, i.e., removed and discarded. If more than 10 percent by weight of the total material is of particle sizes larger than 2-in., the plus 2-in. sizes are removed and replaced (scalped/replaced) with an equal weight of material between the 2-in. and No. 4 sieve sizes. The gradation of the replacement material must be the same relative gradation as that of the total sample between the 2-in. and No. 4 sieve sizes. In the case of cohesionless materials for which the concept of relative density is applicable (less than 5 percent minus No. 200 sieve sizes), EM 1110-2-1906, Appendix XII, Vibrated Density Method specifies either a 6-in. or 11-in. mold diameter (0.1-cu-ft and 0.5-cu-ft, respectively). The 6-in. diam mold is to be used if the maximum particle size is less than 1-1/2 in. and the 11-in. mold is to be used if the maximum particle size is less than 3-in. If the material contains less than 10 percent by weight of plus 3-in. sizes, they are scalped. If the material contains more than 10 percent by weight of particles larger than 3-in., the test is relegated to a research stature and no procedure is suggested.

4. Some of the problems associated with the current USACE procedures as described above are as follows:

- a. The compaction test for earth-rock materials exhibiting moisture-density curves (EM 1110-2-1906, Appendix VIA) is restricted to a maximum particle sizes of 2-in. Many commonly encountered earth-rock mixtures have plus 2-in. fractions which exceed 10 percent of the total material by weight.

b. The EM 1110-2-1906, Appendix VIA, compaction test for earth-rock mixtures requires the use of an 11.5 lb hand-held rammer in the 12-in. mold. This procedure has drawn considerable criticism from USACE Division Laboratories, USACE field construction quality assurance laboratories, and contractor quality control laboratories because they consider it too time consuming and labor intensive. It is a very unpopular test.

c. The scalping with replacement procedure permitted by EM 1110-2-1906, Appendix VIA, for earth-rock mixtures containing more than 10 percent by weight plus 2-in. sizes is now considered undependable as a general "modelling" method to obtain compaction parameters of full-scale gradations. Evidence to support this statement will be provided later herein.

d. There appear to be effects on moisture-density curves obtained in large molds resulting from the larger mold diameter itself, different hammer weights and their relative foot areas, differences in layer thicknesses, or other equipment/procedural factors. These effects will be shown in portions of this report to follow.

e. The EM 1110-2-1906, Appendix XII, relative density test procedure allows up to 3-in. particles in an 11-in. mold. There has been no definitive research to ascertain the effects of this practice.

5. Looking back to the generalized definition of earth-rock mixtures provided in the first paragraph, the typical gradation ranges seen in project files for such materials leads to a fortuitous possibility to arrive at a practical answer concerning the maximum particle size which laboratory tests should accommodate. In overview, the authors observe that it has been relatively infrequent for earth-rock mixtures used in controlled USACE fills to exhibit more than 10 percent by weight of sizes in excess of 3-in. If it is accepted that up to 10 percent by weight can be scalped without introducing significant error in compaction parameters (to be discussed later), then laboratory compaction test procedures validated in molds up to 18-in. in diameter would appear to ordinarily suffice. Additionally, because of complaints against the current method, it becomes prudent to attempt to validate such test procedures using mechanical means of compaction rather than for any version of a hand-held rammer.

6. In consideration of the scale of the problems in the laboratory environment, it is no surprise to discover that earth-rock mixtures also present a plethora of "challenges" in the field construction environment. Of course, the field laboratory faces the testing uncertainties previously

mentioned. Next comes the requirement for an accurate, efficient method for determining the as-compacted fill density and fill water content of soils containing large particles. Then there is the need to compare those values of fill density and water content to appropriate values of maximum dry unit weight and optimum water content to assure that specifications are met, i.e., a quality control or assurance procedure. Because of the rate of fill placement economically necessary in the construction of large fills, it is not feasible to expect to develop complete moisture-density curves for samples of earth-rock mixtures from each fill density test location. Additionally, larger fill density test specimens are required in these materials which translates to greater time and effort per test and fewer tests per work shift. So, it is imperative that the compaction control methodology not only be shortcut in nature but also sufficiently accurate to confirm the specified attributes of the fill.

7. Several versions of compaction control techniques have been utilized by the USACE over the years in dealing with earth-rock mixtures. Fill density tests using direct and/or indirect methods (EM 1110-2-1911, "Construction Control for Earth and Rock-fill Dams, paragraph 5-10) and water content determinations on the total sample have been ordinarily used to obtain the as-compacted parameters but the specifications themselves or the means of relating the as-compacted values to the specifications have generally avoided dealing with the full-scale materials. For example, the specified range for water content and the value of minimum desired percent compaction may be based on the optimum water content and maximum dry unit weight for a fraction of the total material (say, minus 3/4-in. fraction). Then, the water content and dry unit weight of the total fill sample are corrected for the percent "oversize" (percent of total material by weight larger than 3/4-in.) to obtain the water content and dry unit weight of that fraction for comparison to the specified values. Another example would be the use of a scalping with replacement procedure to reduce the maximum particle size for development of the compaction specifications during design. Subsequently, in the fill control procedure, use of so-called one- or two-point compaction tests on scalped and replaced specimens of the total fill sample as described in EM 1110-2-1911, Appendix B, is assumed to be directly equivalent to field testing of the total gradation. These practices, of course, assume that the engineering properties/behavior of the total material will equal or exceed those (in terms of design

requirements) of the selected fraction or scalped-replaced gradation when that fraction or scalped-replaced gradation meets the specified values. In essence, the USBR Rapid Compaction Control Method USBR 7240-89 (USBR 1989a and ASTM 1991a) which has been employed by the USACE on some projects is also predicated on the correction of compaction values of the total material according to the amount of gravel present to obtain those of the minus No. 4 fraction.

Purpose and Scope

8. The purpose of this phase of the general investigation of laboratory testing of soils containing large particles was to develop and verify laboratory test procedures for determining moisture-density relationships for such materials. Specifically, the objective was to develop standard effort compaction test procedures utilizing 12 and 18-in. diam molds and mechanical compaction equipment for earth-rock mixtures having maximum particle sizes up to 3-in and containing sufficient fines (minus No. 200 sieve sizes) to exhibit well-defined moisture-density curves. In addition, it was intended to determine the extent to which Equations (1) and (2) may be utilized to predict the compaction characteristics of full-scale gradations utilizing results of tests performed on finer fractions of the full-scale materials in smaller diameter molds. A subsequent report is to be prepared to address the general issue of compaction control of earth-rock mixtures which exhibit well defined moisture-density curves and to provide guidance concerning fill compaction control methodologies in the light of the findings reported herein. Although WES has recently conducted limited studies involving the determination of maximum and minimum densities of cohesionless, free-draining earth-rock mixtures for which the concept of relative density may be preferred, that data is not considered of sufficient scope to treat herein or in the sequel report on compaction control. The laboratory and field treatment of earth-rock mixtures containing minimal cohesionless fines, whether in their natural in situ state or used as compacted fill, is of particular importance in the earthquake engineering arena and merits a separate and major research effort.

PART II: ACCURACY AND PRECISION OF THE COMPACTION TEST

General

9. It is appropriate at this very early point in a report addressing compaction characteristics of gravelly soils to consider some sobering realities about those fundamental reference values so casually referred to as "THE" optimum water content and "THE" maximum dry unit weight of a soil for a given compactive effort. Both of these parameters are the result of subjective judgment of an individual in the fitting of a compaction curve to laboratory test data typically exhibiting some scatter. Furthermore, the usual test consists of five data points at different water contents which are accepted as sufficient if a smooth curve appears to reasonably fit. Data scatter which would result if several specimens were compacted at each given water content is not indicated unless a point appears to be "out of line" with the other four and a "check" point is ordered. If an experienced and careful technician performs a number of five-point compaction tests on the same material and fits a compaction curve to each data set without cross-reference to the other tests, it is to be expected that ranges in values of optimum water content and maximum dry unit weight will result. Suppose a second technician in the same laboratory is also required to perform multiple tests on the same material using the identical equipment and procedures as the first technician. If the results obtained by both technicians are combined, the total ranges in values of optimum water content and in values of maximum dry unit weight would be expected to be larger than those obtained by either individual. If the two technicians are employed in different laboratories, the observed ranges in the combined data would be expected to be still greater.

10. The occurrence of differences in results obtained by replicate application of a "standard" method to the same material can be addressed within the statistical concepts of accuracy and precision. The applicability of these two concepts to results of compaction tests will be discussed below after presenting the definitions and usages prescribed by the American Society for Testing and Materials, Designation E 177-86 (ASTM 1991b).

Accuracy

11. According to ASTM Designation E 177-86, accuracy is defined according to two schools of thought. One definition is the closeness of agreement between an accepted reference value and an individual test result. The second definition is the closeness of agreement between the accepted reference value and the average of a large set of test results obtained by repeated applications of the test method, preferably in many laboratories. Where the compaction test is concerned, it makes no difference which definition is accepted because there exist no accepted reference values of maximum dry unit weight or optimum water content for any given soil. In other words, there is no accepted reference value for any given soil. Therefore, the concept of accuracy is not applicable to the compaction test.

Precision

12. Precision of a measurement process refers to the degree of mutual agreement between individual measurements from the process. This concept does apply to the compaction test. Furthermore, precision of the compaction test can be categorized according to the cases implied in paragraph 30 above as follows:

- a. Single-operator precision.
- b. Multi-operator precision.
- c. Multi-laboratory precision.

These precision cases would be defined as follows:

- a. Single-operator precision: A measure of the greatest difference between two test results that would be considered acceptable when properly conducted determinations are made by one operator on portions of a material that are intended to be identical, or as nearly identical as possible.
- b. Multi-operator precision: A measure of the greatest difference between two test results that would be considered acceptable when properly conducted determinations are made by more than one operator in the same laboratory on portions of a material that are intended to be identical, or as nearly identical as possible.
- c. Multi-laboratory precision: A measure of the greatest difference two test results that would be considered acceptable when properly conducted determinations are made by two different operators in two laboratories on portions of a material that

are intended to be identical, or as nearly identical as possible.

In this vein, the ASTM currently cites (see Table 1) single-operator and multi-laboratory precision standards in Designations D 698-78 (ASTM 1991c) and D 1557-78 (ASTM 1991d) for results of standard effort and modified effort compaction tests, respectively, employing 4- and 6-in. diam molds. There are no current ASTM Standards for large-scale tests for earth-rock mixtures. ASTM currently bases precision limits on the statistical parameter "difference two-sigma limit" (see ASTM 1991b) which is calculated as follows:

$$\textit{Difference } 2\sigma \textit{ limit} = 1.96\sqrt{2}\sigma = 2.77\sigma$$

where σ is the standard deviation

Given that a variable is normally distributed (random), the probability that any two numbers drawn from the population will not differ by more than some amount can be calculated. Also, for a normally distributed variable, about 95 percent of the values will fall within the range of $\pm 2\sigma$ of the mean value. The intended practical significance of the difference two-sigma limit is that statistically there is about a 95 percent probability that any two numbers drawn at random from among all the measured values will not differ by more than 2.77σ. The ASTM standard then takes the difference two-sigma limit of 2.77σ and expresses it as a percentage of the mean value of the variable. The impact of ASTM precision standards for 4-in. and 6-in. mold diameters should they be applied to larger diameter mold tests on a typical earth-rock material can be indicated. A typical earth-rock mixture may exhibit a maximum dry unit weight around 130 pcf and an optimum water content around 7 percent. The single-operator precision stated in Table 1 for maximum dry unit weight would be 1.9 percent of 130 pcf or almost 2.5 pcf absolute difference between the two values. The single-operator precision of Table 1 for optimum water content would be 9.5 percent of 7.0 percent or 0.7 percentage points absolute difference between the two values. Considering the multi-laboratory case, such as between the USACE quality assurance lab and the contractor's quality control lab, 4.2 pcf absolute difference in maximum dry unit weight and 1.0 percent absolute difference in optimum water content would be acceptable under ASTM current standards. The key phrase in the definition(s) of precision is "when properly conducted determinations are made.... on portions of a material intended to be identical". A proper testing program to determine precision limits for the compaction test is a very costly and complex undertaking. There must be careful attention to test materials, all associated methods such as moisture curing of specimens, calibration of all equipment to the same reference standards, etc. After all, the question is the repeatability of results from the test method, not the degree of poor laboratory practice. It is logical that multi-laboratory precision cannot be addressed until the question of single-operator precision has first been resolved. It makes no sense to accept any values in the multi-laboratory study that have not met the single-operator precision. This would dictate acceptable replicate single-operator tests in each participating laboratory with perhaps the average values reported for the multi-laboratory case. To the best of the authors' knowledge the current ASTM precision standards were not derived in this manner.

13. It is valuable at this point to interject a review of three testing programs pertinent to the question of precision in compaction testing. However, none of these studies meet all the criteria stated above as necessary to establish general multi-laboratory precision standards for the compaction test.

14. The first study was initiated in 1964 under the auspices of the American Council of Independent Laboratories (ACIL) and was aimed at obtaining an indication of variation in test results among commercial laboratories pertaining to Atterberg limits, optimum water content and maximum dry unit weight by Standard and Modified efforts, specific gravity of solids, and grain-size distribution. With respect to compaction tests, the only requirement imposed was the use of ASTM Designation D 698-58T, Method A, for standard effort and Designation D-1557-58T, Method A, for modified effort. There were no other controls imposed. To achieve these objectives, three "standard" soils were selected to be provided to all participating commercial laboratories. The three soils were designated as Vicksburg loess (ML), Vicksburg lean clay (CL) and Vicksburg buckshot clay (CH). Preparation of the standard samples was accomplished by WES at the request of and assisted by ACIL. Under the supervision of ACIL personnel, the three materials were carefully processed at WES and placed in 333 sealed containers weighing 80 lb each and stored under cover to await shipment to the requesting commercial laboratories. Three "umpire"

laboratories were designated by ACIL and included WES, U.S. Bureau of Public Roads, and Massachusetts Institute of Technology. These umpire laboratories ran 4 to 5 replicate compaction tests on each sample. Approximately 100 commercial laboratories participated in the program although all laboratories did not perform all of the test suite. However, 98 of the labs performed standard and modified effort compaction tests on the ML and CH samples and 97 labs developed compaction curves for the CL sample. The discrete data obtained from the program are reported and analyzed statistically by Hammitt (1966). Figures 1 through 3 present the results of the standard effort tests obtained by the commercial laboratories for the ML, CL, and CH samples, respectively, as replotted by the authors. Also shown in these figures and in Table 2 are the ranges and mean values obtained by the umpire labs. The modified effort data are not treated in detail because they were not appreciably different in scatter patterns. The statistical summaries for the commercial laboratory results are given in Tables 3 through 5. The scatter of the data seen in Figures 1 through 3 reveals the magnitude of the problem of specifying acceptable precision for compaction test parameters based on an essentially uncontrolled testing program. It is obvious from Figures 1 through 3 that some laboratories did not properly conduct the test. But, how many of the test data are the result of poor practice? If the acceptable precision is based on the standard deviation for all the test data for a given soil type among Figures 1 through 3, it will be a "sloppy" standard. Table 6 shows the difference two-sigma precision limits for maximum dry unit weight and optimum water content calculated for each of the ACIL data sets of Figures 1 through 3 as dashed boxes. The precision limits specified by ASTM Designation D 698-78 are also shown in these figures. Scatter of the compaction data clearly varies with soil plasticity with the CH soil exhibiting the greatest dispersion (largest standard deviations) and the ML soil exhibiting the least. Note from Table 6 that while the difference two-sigma limit for maximum dry unit weight in pcf obviously must track the trend in standard deviation, the limit stated in terms of percent of mean value do not because of the relative values of the mean maximum dry unit weights. Also note that use of a single precision range as a percent of mean value as the ASTM currently specifies, runs counter to the trends for maximum dry unit weight indicated by the ACIL study. In other words, a fixed precision for all soil types would force a smaller acceptable difference between two values of maximum dry unit weight obtained for a CH soil which is most difficult to obtain consistent values for and a more generous difference allowance for ML and CL soils which showed less data dispersion. If the precision limits indicated for the CH soil were adopted for all soil types, this would aggravate the already sloppy practice of accepting all data as equally correct in calculating precision limits. It is seen from Figures 1 through 3 that the current ASTM multi-laboratory precision limits for maximum dry unit weight are somewhat more restrictive compared to the values calculated from the ACIL data, especially for the CH soil. With respect to multi-laboratory precision of optimum water content, it is seen that the current ASTM standard is similarly more restrictive than the limits calculated using the ACIL data. However, the optimum water content precision limits stated as a percent of mean value are the greatest for the more problematical CH soil because that soil exhibits the highest values of optimum water content. It is to be noted that the standard deviations for both maximum dry unit weight and optimum water content from the ACIL data generally exceed the specified maximum values of ASTM Designation D 698-78 (see Table 1). An inconsistency exists in the ASTM standard in that both standard deviation and difference two-sigma precision limits as a percent of mean value are stated for the multi-laboratory case. If the standard deviation restriction is accepted as the reference, then the precision range as a percent of mean value must be a variable because the mean value varies (or vice versa). If the precision were stated as a range in maximum dry unit weight in pcf or as a range in optimum water content in percentage points, there would be no inconsistency since these are fixed values calculated as 2.77σ.

15. Concurrently with the ACIL study among commercial laboratories, the USACE decided to have its Division laboratories also test the standard soil samples. Strohm (1966) reports the results obtained among ten Division Laboratories. Figures 4 through 6 show the standard effort compaction data for the standard soils. Since this study predated the first edition of EM 1110-2-1906 which standardized equipment, the data reflect a mix of compaction equipment as indicated in the figures. Scatter in the USACE data for both optimum water content and maximum dry unit weight increased with plasticity of fines as did the commercial lab results previously discussed. As was done for the commercial lab results, both the difference two-sigma precision limits calculated from the standard deviations of the data and those specified currently by ASTM are shown in Figures 4 through 6 as dashed boxes. The values

calculated from the standard deviations of the data are tabulated in Table 7. For the standard ML soil, precision calculated as above would be 9.8 percent of the mean value for optimum water content and 2.1 percent of the mean value for maximum dry unit weight. For the standard CL soil, the precision was 13.2 percent of the mean value for optimum water content and 2.7 percent of the mean value for maximum dry unit weight. For the standard CH soil, precision was 22.3 percent of the mean value for optimum water content and 4.0 percent of mean value for the maximum dry unit weight. So, on the average, the multi-laboratory precision achieved by the USACE labs for optimum water content was about equivalent to the current ASTM standard but the precision achieved for maximum dry unit weight was equal to or better than the current ASTM requirements (despite variation in equipment).

16. It is reasonable to consider the ACIL umpire laboratory results as a multi-laboratory study in its own right. Unfortunately, as seen in Table 2, standard deviations were not reported for those data. However, the ranges of the data were reported. For data which are normally distributed (random variable), 99.7 percent of the data fall within ± 3 standard deviations (σ) of the mean and 95.5 percent of the data fall within ± 2σ. Taking a conservative approach, a very crude estimate of the standard deviations of the umpire laboratory data can be made by taking the respective ranges to be equivalent to 4 times the respective values of σ. If this is done and difference two-sigma precision limits are calculated for the ACIL standard soils accordingly, the limits seen in Table 8 result. From Table 8 it is seen that the multi-laboratory precision limit stated as a percent of mean value for maximum dry unit weight are only about one-half the current ASTM standard while the limits calculated for optimum water content are anywhere from about one-fourth to one-half the current ASTM value.

17. The third study (Sherwood 1970) consisted of single-operator, multi-operator and multi-laboratory compaction and soil classification testing organized by the British Road Research Laboratory (RRL) involving itself and 39 other government, university and private testing laboratories. The only condition imposed upon the laboratories was that British Standard 1377:1967 was to be employed for all test methods. The soils selected by RRL for the study were a sandy clay, CL, (LL=36, PI=19), Gault clay, CH, (LL=75, PI=26) and Weald clay, CH, (LL=68, PI=25). These materials were carefully processed and batched for distribution to the participants in a fashion similar to that

used for the "standard" soils of the ACIL study. Compaction tests equivalent to standard and modified efforts were performed among the participants. Thirty seven of the 40 labs provided results for the sandy clay (CL) and 38 labs tested the Gault and Weald clays (CH). The results of the standard effort tests are shown in Figures 7 through 9. The difference two-sigma precision limits calculated from the standard deviations of the data for the various cases addressed by RRL are given in Table 9. The calculated precision limits and the ASTM precision limits relative to the multi-laboratory data are shown as dashed boxes in Figures 7 through 9. Figures 7 through 9 show that the RRL data exhibit scatter similar to that seen in the ACIL study for the CL and CH soils. The standard deviations relative to maximum dry unit weight for the RRL data were slightly lower than those seen for the ACIL data. These comparative dispersions were not strictly consistent with differences in plasticity index since the RRL clay (CL) was more plastic than that tested in the ACIL study, but the two clays (CH) of the RRL study were both less plastic than that tested in the ACIL study. The dispersion of the optimum water content data was about the same for the two CL soils between the two studies but the standard deviations for the two RRL clay (CH) soils were greater than that for the ACIL clay (CH) soil.

18. The single- and multi-operator precisions obtained by the RRL are also shown in Table 9. An expectable tre d in improving precision is seen from multi-laboratory to multi-operator to single-operator for both maximum dry unit weight and optimum water content for the Gault clay which was the only soil replicate tested by the single-operator. It is seen by comparing Tables 8 and 9 that it appears that the three ACIL umpire laboratories probably at least matched the RRL single-operator precision for both compaction parameters.

19. In speaking of relative dispersions of the data among the cases discussed above, there is more to the question than simple comparisons of the numbers. Figure 10 reveals an apparent relationship between standard deviations and numbers of laboratories participating for the CL and CH soils. The RRL data seem to fit well with the ACIL data probably because the CL and CH soils tested by RRL were not to different from the ACIL soils with respect to classification indices. The authors suspect that the lower standard deviations achieved by the 10 USACE Division labs and the estimated values for the ACIL umpire labs actually reflect a greater consistency of practice and care

exercised in performance of the tests by those labs as compared to the "catch-all" nature of the RRL and ACIL commercial lab results. It should be remembered that no verification of adherence to the standard method was required in their large studies. Anyway, it appears that it is reasonable to expect that two laboratories performing the test carefully with properly calibrated equipment and in exact conformance to the published standard can achieve results consistently much closer together than indicated by precision limits derived from data produced by a large number of organizations.

20. In the final analysis, it appears that precision of the compaction test is currently a matter of opinion. The ASTM is contemplating an extensive cooperative program to address precisions of a number of laboratory soil tests. Until better precision standards are forthcoming, the authors offer the opinion that it is practical to expect that two laboratories can obtain values of maximum dry unit weight on the same material which routinely do not differ by more than 2.0 pcf and values of optimum water content which do not differ by more than 1.0 percentage point. That opinion is qualified by the critically important stipulation that both laboratories vigorously follow the standard methods (including the associated equipment) and have calibrated all the pertinent equipment to the same appropriate reference standards. Based on their experience gained with earth-rock mixtures in the conduct of this investigation, they are willing to hold to that opinion for large-scale compaction tests performed with a mechanical compactor with two caveats. Since there are no current standard procedures and mechanical equipment specifications offered by anyone for large-scale tests, there must be a specific procedure used by both laboratories and the two mechanical compactors must be configured and calibrated to some identical standards. Hereafter in this report, the authors will occasionally state some precision used in judgment of data trends. It will be nothing more than a matter of their opinion.

21. The USACE has endorsed the use of National voluntary standards in the conduct of its mission. ASTM standards fall in this category and are more and more often referred to in USACE construction specifications. Therefore, the question arises as to how precision standards on compaction test results or, perhaps eventually, even on fill density test results may affect the writing and application of specifications for compacted fills. It is to be remembered that under such standards, when two test results fall within the accepted precision range of each other, neither can be considered more correct

than the other. For a single example among several possible scenarios, what is to be done if the quality control (contractor) laboratory test results show the compacted material to conform to the specifications while quality assurance (Government) laboratory test results do not, but both results fall within the precision range for the test? For that matter, the vice versa case could occur. The question has alternative answers which would include:

a. Accepting the more favorable result which would avoid the cost and time of reworking and retesting the lift.

b. Accepting the more conservative of the results, i.e., that which indicates the lower percent compaction and that which indicates the greatest deviation of fill water content from optimum.

c. Defining the Government's test results as the determinate ones.

Whichever approach is selected, it would be necessary to spell it out in the job specifications. Otherwise, if test standards containing precision are cited in the specifications without clarification, the stage is set for contest with the contractor during construction which could have been easily avoided.

PART III: REVIEW OF PREVIOUS RESEARCH

Introduction

22. Before entering into summarization of selected past investigations, it is desirable to orient the reader with respect to the complexities involved in research to ascertain properties or behavior of soils containing large particles. In facing the generalized question, " What are the effects of large particles on the compaction characteristics of earth-rock mixtures?", the investigator is immediately thrust into a pandora's box of possible variables such as:

a. Maximum particle size.

b. Character of aggregate,i.e., hardness, durability, etc.

c. Range in gradations.

d. General shape of gradation curves.

e. Particle shapes.

f. Percent fines, i.e., Minus No. 200 fraction.

g. Plasticity of fines.

h. Procedure for preparing test gradations.

i. Equipment specifics, particularly for full-scale tests.

j. Specific comparative procedures.

k. Number of replicate tests as checks.

l. Precision relative to all of the above.

m. Etc.

Because of the cost and time constraints usually associated with such work, decisions have to made with respect to variables addressed with an imperfect realization of restrictions which should be imposed on conclusions by exclusion of investigation of effects of some of the variables. Given any two independent investigators, it can be expected that they might choose different combinations of selected variables in their judgment of those considered most important within the framework of time and cost constraints. The end result is that one investigator may conclude that a given procedure works fine while the other investigator concludes it doesn't. In fact, they may both be correct which only means that for some materials it suffices and for others it doesn't. Of course, there is also the possibility that one or both failed to account for some variables' interrelationship which, if treated, would have led both to the same conclusion. So it is in this frame of mind that an overview of selected previous investigations is given below.

23. Within the last 25 years very few studies have been directed at major comparative testing of earth-rock mixtures to evaluate the propriety and accuracy of practices to obtain engineering properties. There have been instances where project specific materials have been extensively tested but not in a comparative manner utilizing different procedures and equipment sizes or by methodically separating variables. In the interest of efficiency, the authors will address only five past studies which are specifically selected for the purpose of transitioning the reader from earlier findings into recent times in a manner that will illustrate some of the problems discussed in the previous paragraph and set the stage for the new work reported herein. These previous investigations are described in a report by the USBR (1963), a paper by Gordon, Hammond and Miller (1965), two reports by Donaghe and Townsend (1973 and 1975) of the US Army Corps of Engineers Waterways Experiment Station (WES) and the article by Garga and Madureira (1985).

Findings of Previous Investigations

USBR (1963)

24. In 1963, the USBR reported the results of a study on the compaction characteristics of soils containing gravel in varying amounts from 0 to 50 percent by weight. The soil samples used in the study were synthesized by combining a lean clay soil from Twin Buttes Dam, Texas, with a subangular to subrounded sand and gravel from Yellowtail Dam, Montana. No information is given in the report concerning the exact procedures used in batching the samples or in managing water content. These two soils were combined in various proportions to produce the 10 research gradations shown in Figure 11A which span a broad range in maximum particle size, percent sand and percent gravel and percent minus No. 200 sieve sizes. The gradation of the minus No. 50 fraction used in all of the mixtures is shown as Sample No. 36R-10, Figure 11A. The gradations of the plus No. 50 fractions which were combined with Sample No. 36R-10 to form the other nine test gradations are shown as dashed curves in Figure 11B while the solid curves are the gradations of the plus No. 4 material for those test samples containing gravel, i.e., Samples No. 36R-1, 2, 3, and 4. If the coarsest gradation of Figure 11A, i.e., that one

with a maximum particle size of 3-in., is taken as the basis of reference, it is seen that the other gradations would be obtained by successive scalping. Standard Proctor and large-scale (standard effort) compaction tests for soils containing gravel were performed in accordance with Designations E-11 and E-38, respectively, of tł " BR Earth Manual, First Edition, 1960. The Standard Proctor test utilized a 4.0-in. diam 1/20 cu ft compaction mold. The large-scale compaction test utilized a mechanical compactor and a 20-in. diam by 11-in. tall compaction mold although the specimen was compacted in three layers to a total height of 9 in.

25. The pertinent findings of the study are summarized as follows:

a. Figure 12 presents the standard effort compaction curves obtained for the ten test gradations of Figure 11A. Viewing the test gradations as the product of successive scalping, it is seen that such a procedure results in a consistent decline in maximum dry unit weight and an increase in optimum water content. Figure 13 presents the same data. It can also be said that this trend is observed as the coarse fraction (however one wishes to define it) becomes less well graded or more uniformly graded. It is timely here to make a point to aid the reader in beginning to follow the effects of varying the gradation of an earth-rock mixture. The popular procedure of scalping with replacement also produces a more uniform gradation of the coarse or "oversized" fraction. It will be shown later that the same result is obtained, i.e., a lower maximum dry unit weight and higher optimum water content as compared to the parent full-scale gradation.

b. Figures 13 and 14 illustrate that the USBR also observed differences between compaction curves obtained on the same gradation in different size molds and by hand rammer as opposed to mechanical compactor. For the gradations with No. 4 and 3/8 in. maximum particle sizes, significantly different values of maximum dry unit weight and optimum water content were obtained between the 4-in. and 20-in. diam molds. This explains the discontinuities seen in the plotted trends of Figure 13. It is clear that although the total applied compactive effort was identical for both molds, the efficiency of the applied energy or methodology in densifying the material was greater in the large mold. This is all that can be said since all sorts of other variables are involved between the 4 in. and 20-in. mold procedures such as hammer weight, hammer foot size, layer thicknesses, etc. Figure 14 indicates that only minor differences were seen between the hand rammer and mechanical compactor tests performed in the same mold (4-in.) which were confined to the dry side of optimum and did not result in a shift in the values of maximum dry unit weight and optimum water content.

c. The USBR report also addresses the applicability of Equation 1) in the compaction control of gravelly soils. Figure 15 is a plot of results obtained in a previous study (USBR, Holtz and Lowitz 1959) using a material containing well-graded gravel (No. 4 to 3-in., with all sizes represented) and shows that there was no significant decline in the calculated dry unit weight (expressed as percent compaction) of the minus No. 4 fraction below a gravel content of about 30 percent. However, Figure 16 presents the same results for the minus No. 4 materials tested in the large mold in the 1963 study for which the gravels were somewhat more poorly graded and shows that "particle interference" began at gravel contents lower than 10 percent. The concept of "particle interference" will be discussed later herein. The second curve of Figure 16 is a similar analysis pertaining to the variation in dry unit weight of the minus No. 50 fraction of compaction specimens with up to 3/8-in. maximum particle size and compacted in the 4-in. mold. The left-hand portion of Curve B, where the sand in the mixture is poorly-graded, shows that "particle interference" begins at less than 10 percent sand. However, the right-hand portion of curve B, where the sand becomes more nearly well-graded, agrees fairly well with respect to percent compaction of the fine fraction with the corresponding portions of the curves shown in Figure 15 for the mixtures containing more well-graded gravel. Therefore, it was concluded that the gradation of the gravel was almost as important as the percent gravel.

26. Since the term "particle interference" has arisen and will be used regularly later in this report, it is appropriate to address the concept as the USBR authors defined it. The concept of "interference gravel content" has been bandied about through the years leaving in its wake confusion and various degrees of disagreement. The authors will turn to an argument of the concept and provide their own definition at an appropriate point later in this report. Within the USBR 1963 report the authors state their opinion as follows:

> "Compaction tests have shown that if the gravel content is very small, the density of the fine fraction is not affected by the presence of the gravel. At a certain gravel content, henceforth referred to as the critical gravel content, the gravel particles come into contact and interfere with each other. The critical gravel content varies with the gradation of the gravel. At all gravel contents less than the critical gravel content, the density of the fine fraction is nearly constant and equal to the density with no gravel present, and the density (of the fine fraction) can be calculated by assigning all of the voids to the fine fraction."

There was a very specific meaning attached to gravel particles interfering with one another as clarified in Figure 17. There it is seen that it was envisioned that voids would develop between groupings of gravel particles. Furthermore, it was implied in the report by absence of any other plausible explanation that these voids were the sole reason for decreasing calculated dry unit weight of the fine fraction with all voids associated with it. To attempt to accommodate such a condition, there were procedures suggested for associating a portion of the total voids with the gravel fraction for gravel contents above the critical value. The authors choose not to enter into treatment of those procedures because they do not believe them to be reliable or practical. Furthermore, it will be shown later that the development of partially filled or completely open voids between gravel particles is not usually observed until gravel contents exceed 60 to 70 percent by weight. Gradations containing such high gravel contents are not often best compacted by impact methods in the laboratory, i.e., are more likely to be best treated by the relative density concept or at least by vibratory compaction. In their personal experience and in their review of the literature, the authors have not encountered materials containing more than 10 percent fines (minus No. 200 sieve fraction) and gravel contents in excess of 70 percent used in major embankments. Compaction characteristics of such gradations are beyond the scope of this report.

Gordon, Hammond and Miller (1965)

27. These authors report results of compaction studies conducted by the California Department of Water Resources (CDWR) on the gravelly soil selected for placement in the impervious core of Oroville Dam. The material studied was obtained from a borrow area in an alluvial deposit and was fairly well-graded over a gradation range of gravelly, clayey sand to clayey, sandy gravel containing up to 65 percent by weight of gravel sizes. The gravel was of sound mineralogy and varied from subrounded to subangular in particle shape. The material gradings in the borrow area fell into four major groupings as shown in Figure 18. These groupings were studied by selecting representative samples as indicated in Table 10. Maximum particles sizes investigated were 4, 3, 1-1/2, and 3/4-in. and No. 4 sieve size (3/16-in.). The 3-in. maximum particle size gradations were most carefully examined because the Oroville Dam specifications required scalping of the borrow material before placement at this size. It is seen from Table 10 that the test program was based on successive scalping. The gradations designed to study the 3-in. maximum particle size cases (sample Nos. 1-4687 and 2-890) were artificially composed by adding

various percentages of gravel to each of two samples of minus No. 4 material. Classification and other physical data pertinent to various fractions are given in Table 11. Laboratory sample preparation consisted of first separating the material on the No. 4 sieve. The gravel fractions were stored in vats of water, while the minus No.4 fractions were air-dried and placed in 55-gal drums. Approximately 24 hr prior to performance of a compaction test, the minus No. 4 fraction was wetted to predetermined moisture content and allowed to cure. Where plus No. 4 sizes were needed in the test gradation, the prewetted minus No. 4 fraction was combined with the gravel in its saturated surface-dry condition just prior to compaction. For each compaction specimen containing gravel, the material was batched by layer to eliminate variations in grading.

28. The compaction equipment summarized in Table 12 included a variety of mold diameters and hammer weights coupled with procedures to yield an intermediate (between standard and modified efforts) compactive effort of 20,000 ft-lb/cu ft (an apparent CDWR standardized test effort of the time). Interestingly, as a result of this test program a large-size mechanical compactor was developed and installed in the Oroville Dam field compaction control laboratory. It was designed to handle material with up to a 3-in. maximum particle size and to deliver 20,000 ft-lb/cu ft compactive effort in a 12-in. diam mold with a 127.5-lb hammer. The equipment then permitted a mold diameter to maximum particle size ratio as low as 4. California Department of Water Resources standard procedure (20,000 ft-lb/cu ft) for compaction tests on minus No. 4 material is seen from Table 12 to have included a 1/20-cu ft mold, a hammer weight of 10-lb, a height of hammer drop of 18-in, and a total of five compaction layers with 13 blows per layer.

29. Pertinent observations and conclusions relative to the work by Gordon, Hammond and Miller are summarized as follows:

- a. Compaction curves of the minus No. 4 fractions of samples representative of Gradings B, C, and D, with data for comparison of gradation, specific gravity, and plasticity, are shown in Figure 19. These curves indicate that the maximum dry unit weight of the fractions may be more sensitive to plasticity in the sense of distance above the A-line than to gradation (see the plasticity chart inset of Figure 19). The actual differences in gradation were small, the maximum variation in any particle size being only about 15 percent by weight. Between curves C and D, however, there was as much as 8 lb/cu ft difference in maximum dry unit weight. Gordon, Hammond and Miller also concluded that this marked effect of plasticity carried over when gravel was added but to a lesser degree. The greater the distance of the plasticity data above the A-line, the higher the maximum dry unit weight.

b. Figure 21 shows the compaction curves of each of the gradations for each sample shown in Figure 20. Examination of Table 12 indicates that there may be effects of mold sizes, hammer weights and procedures on the curves of Figure 21 which cannot be accounted for utilizing the data presented. It is safe to say that maximum dry unit weight increases and optimum water content decreases with increasing gravel content. The relative amount of increase in maximum dry unit weight decreases with each increment of increasing gravel content. As indicated in Figure 21 by samples 1-4046 and 1-4047A, this trend continues until an "optimum" gravel content is reached above which the maximum dry unit weight begins to decline. It is also observed from Figure 21 that at higher gravel content the compaction curve may shift significantly in shape and position relative to those obtained at lower gravel contents. This occurrence certainly implies a major alteration in the effects of applied energy with a comparatively small additional presence of gravel.

c. Figure 22 shows the results of applying Equation (1) utilizing the maximum dry unit weights of two minus No. 4 fractions of differing plasticity to predict that of the full-scale material. These data were derived from the test series performed on the artificial gradations with 3-in. maximum particle size (see Table 10, samples 1-4687 and 2-890). It is seen that the predicted (theoretical) values were satisfactory up to some limiting gravel content in the full-scale gradation (empirical values). The limiting gravel content for sample 1-4687 with a CL minus No. 4 fraction was apparently only about 6 percent while for sample 2-890 with a CL-ML minus No. 4 fraction it was about 34 percent. Holtz and Lowitz (1957) had shown the limiting gravel content to be 44 percent for a clayey gravel and 36 percent for a silty gravel. The materials of Figure 22 plot about halfway between those tested by Holtz and Lowitz. The disparity evident in these comparative findings may indicate that limiting gravel content cannot be estimated on the basis of plasticity of the minus No. 4 fraction.

d. Gordon, Hammond and Miller attempted to get around limiting gravel content with respect to applicability of Equation (1) as a fill compaction control tool by plotting the ratio of full-scale maximum dry unit weight to that of a designated smaller maximum particle size versus the percent gravel larger than the designated size as shown in Figure 23. For the minus No. 4 fraction data this becomes the ratio of the full-scale minus 3 in. maximum dry unit weight to that of the minus No. 4 fraction versus the percent gravel. Because the minus No. 4 fractions were not extremely different in plasticity (Table 10, samples 1-4687 and 2-890), it was expected that only one relationship would be developed which would make for a powerful means in the field to accurately predict maximum dry unit weight of the full-scale material from that of the minus No. 4 fraction. However, as seen in Figure 23, two significantly different curves resulted from the relatively small differences in plasticity and grading of the fractions. This is not to say that this approach isn't feasible if the range of borrow materials results in only a few such curves which can be clearly identified in some manner with the particular material taken from the fill during a routine quality control fill density test. The significance of plasticity seen here and discussed in a. above should be borne in mind as the work of Garga and Madureira is reviewed later herein. The third curve shown in Figure 23 is for the minus 1-1/2-in. fraction and is much flatter than those for the minus No. 4 fractions and indicates ratios of only a little more than 1.0 up to the maximum of 25 percent plus 1-1/2-in. typical of that in the range of borrow soils. These small differences are not surprising in consideration of the small degree of scalping. It would be expected that a curve developed for the minus 3/4-in. fraction would be intermediate between the minus 1-1/2-in. and minus No. 4 fractions.

e. Gordon, Hammond and Miller also looked closely at the relationship of minus No. 4 moisture content to total sample dry unit weight. The objective was to identify the water contents required in the minus No. 4 fraction to achieve optimum water contents (or maximum densities) for mixtures resulting from the addition of various percentages of saturated surface-dry gravel. To achieve this, compaction characteristics of the minus No. 4 fraction were first determined within a plus or minus 1-1/2 percentage point tolerance of the following points on the compaction curve: (1) optimum minus 1 percentage point, (2) optimum, (3) optimum plus one percentage point, and (4) optimum plus 2 percentage points. These ranges were then compared to the resulting ranges on the compaction curves for the gravelly total samples. Figure 24a through 24d present the results. The dark bands represent the corresponding ranges on the compaction curves. The writers wish to emphasize an important point illustrated by these data which can have major impact on quality control/assurance practices. For a given range in water content of the minus No. 4 fraction, the resulting range in water content of the total material is smaller. This can also be seen using Equation (2) by assuming some gravel content and gravel absorption and then calculating the range in total sample water content for a given range in minus No. 4 water content. So, if water content specifications are developed around some fraction of the typical total materials, the specified range is applicable only to that fraction. If the same range is accepted for the total material during construction, then an inadvertent relaxation of water content specifications has occurred.

f. Figures 24a through 24b also show that compaction curves for total materials become increasingly more sharply peaked with addition of gravel. In other words, the dry unit weight achieved by a given compactive effort becomes increasingly

> sensitive to moisture content. Should water content specifications be predicated on the total material and span only 3 to 4 percentage points, fill water contents should then be taken on the total material removed during a fill density test or great care should be exercised concerning the value of gravel water content to be used in Equation (2) to calculate total material water content from more convenient tests performed on, say, the minus No. 4 fraction.

Donaghe and Townsend (1973)

30. The first investigation reported by Donaghe and Townsend (1973) included comparative standard effort compaction tests based on a naturally occurring earth-rock mixture from a borrow pit utilized in the construction of DeGray Dam, Caddo River, Arkansas. The gradation of that material is given in Figure 25 along with two scalped/replaced gradations derived from it and the gradation of the Minus No. 4 fraction common to all. It is important to note immediately that the gravel content of the soil was relatively high at 47 percent. The test material can be described as a clayey, sandy, gravel with maximum particle sizes of about 3-in.; the minus No. 40 fraction had Atterberg limits of LL=37 and PL=14. The gravel particle shapes varied from subangular to subrounded as the particle size increased. A thorough description of the DeGray Dam, the range in earth-rock mixtures used in its construction, and the compaction control procedures employed are given by Strohm and Torrey (1982). Batches for the test specimens were prepared by thoroughly mixing a predetermined amount of air-dry minus No. 4 material with a measured quantity of water. The moistened minus No. 4 material was then stored in airtight containers and allowed to cure for a period of at least 16 hr. The plus No. 4 material required for each batch was prepared by combining the air-dry portion of material required for each sieve and then storing the resulting material in containers filled with water. Immediately prior to compaction, the cured minus No. 4 fraction was mixed with the saturated-surface-dry aggregate. Except in tests using the 4- and 6-in. molds, each layer to be compacted was batched separately to prevent variations in gradings between layers.

31. The compaction equipment included a mechanical compactor manufactured by the Howard Company (see Figure 26) and equipped with 18-, 12- and 6-in. diam molds and 5.5- and 24.7-lb rammers having diameters of 2.0 and 6.0 in., respectively. The unadjustable configuration of the mechanical compactor was such that standard effort (12,375 ft-lb/cu ft) could not be precisely applied. The discrepancies are considered to be insignificant relative

to the conclusions drawn. Table 13 shows the minor differences involved along with other data pertinent to mold sizes, rammer sizes and compaction procedures. Equipment used for comparative tests with the hand-held rammer in 4- and 6-in. molds conformed to that described in EM 1110-2-1906, "Laboratory Soils Testing", Appendix VI.

32. The pertinent findings relative to the Degray gradations are shown in Figures 27 and 28 and summarized as follows:

a. As in the case of the USBR study discussed above, use of the mechanical compactor and the hand-held rammer on the same gradation in the same size mold resulted in minor differences in the compaction data obtained. The USBR tests indicated differences only on the dry side of optimum water content and no effect on the values of maximum dry unit weight and optimum water content (see Fig. 4). However, Donaghe and Townsend reported a shift in the entire compaction curve for the scalped/replaced minus 3/4-in. material in the 6-in. mold as seen in Figure 27, curves A and B. The mechanical compactor yielded a maximum dry unit weight 1.2 pcf higher than the hand-held rammer and an optimum water content 0.5 percentage points lower. Even though these differences are not significant with respect to test precision (to be discussed later), the mechanical compactor Curve B gives the appearance of having been the result of a slightly greater compactive effort even though every element of the tests were identical (even the diameters of the rammers' feet) other than mechanical versus hand-held rammer. The explanation for these differences probably lies in the design of the USACE hand-held rammer of that time which consisted of a free falling weight which impacted upon a fixed foot which rested upon the soil. It was discovered that this arrangement imparted less compactive effort compared to a rammer which permitted direct impact of the falling weight upon the soil. A study was conducted (Horz 1983) and EM 1110-2-1906 was revised in August, 1986, to specify the hand-rammer of ASTM, Method D 698 which allows the falling weight to directly impact upon the soil. The differences in compaction curves observed by Horz as produced by the old CE rammer and the current rammer were commensurate with the magnitude of differences between Curves A and B of Figure 27. Therefore, it is likely that the more correct compaction curve for the minus 3/4-in. material obtained in the 6-in. mold was that produced by the mechanical compactor, i.e., Curve B of Figure 27. However, it is to be noted that there is a very subtle difference in the slope of the dry-side portion of Curves A and B, with the mechanical compactor (Curve B) exhibiting a slightly flatter slope as was also observed, although to a greater degree, by the USBR in the 1963 report (see Figure 14). It is also pointed out that the compaction curve for the minus No. 4 fraction (Curve C, Figure 27) also must reflect the lower compactive effort imparted by the old USACE rammer design.

b. Differences were observed between compaction curves obtained on the minus 3/4-in. scalped/replaced gradation utilizing the mechanical compactor in the 6- and 18-in. molds. These curves are those designated Curves B and D in Figure 27. While the total effort applied was identical, it is obvious that the efficiency of the applied energy was greater in the 18-in. mold than in the 6-in. mold. Both mold diameter and rammer foot diameter must be considered as involved even though the ratio of rammer foot diameter to mold diameter was identical (1/3) in both tests. This effect results in a discontinuity in the relationships among maximum dry unit weight and optimum water content versus maximum particle size seen in Figure 28 and also previously reported by the USBR (see Figure 13). The maximum dry unit weight obtained in the 18-in. mold was 2.2 pcf higher and the optimum water content was 0.8 percentage point lower than the corresponding values obtained from the 6-in. mold.

c. Looking at only the mechanical compactor curves of Figures 27 and 18, it is seen that the maximum dry unit weight decreased and the optimum water content increased with application of the scalping with replacement procedure to produce successively smaller maximum particle size. The trend is traced in Figure 27 from the full-scale gradation (Curve E) to the minus 2-in. (Curve F) to the minus 3/4-in. (Curve B). The principal effect is not simplistically attributable to change in maximum particle size, but also to the alteration of the gradation of the gravel fraction. Remembering that all of the gradations contained the same minus No. 4 fraction and percent gravel content by weight (see Figure 25), one feasible point of view is that increasing uniformity of the gravel fraction produced the observed trend. It must also be borne in mind that increasing uniformity at constant percent gravel as maximum particle size decreases is equivalent to a rapidly growing total number of gravel particles present in the mix. Since the weighted value of specific gravity of the mixture (see EM 1110-2-1906, Appendix IV), i.e.

$$G_{mix} = \frac{G_s G_a}{f G_a + c G_s}$$

where

f - percent minus No.4 expressed as a decimal

c - percent gravel expressed as a decimal

G_s - specific gravity of solids

G_a - apparent specific gravity of gravel

does not change, the decrease in dry unit weight as maximum particle size decreases cannot be attributed to such an effect. Maximum dry unit weight versus optimum water content trends down a "line of optimums" with the degree of saturation remaining consistent in comparison to the zero air voids curve (100% saturation), suggesting that the efficiency of the applied compactive effort declines as the gradation of the gravel becomes more uniform. On the other hand, if the decline in maximum dry unit weight reflects the development of inordinate voids among groupings of gravel particles (the USBR concept of "particle interference"), it seems logical that changes in degree of saturation at optimum water content would have created some other obviously different trend.

Donaghe and Townsend (1975)

33. In their second report (1975), Donaghe and Townsend present the findings of an investigation primarily directed at:

a. Determining the validity of the scalping and replacement procedure.

b. Evaluating the usefulness of Equation (1).

The gradations of the artificially blended compaction test samples are given in Figures 29. The test gradations were generated by maintaining the percent fines (minus No. 200 sieve) constant at 25 percent while varying the sand and gravel contents to achieve mixtures with a maximum particle size of 3-in. and gravel contents ranging from zero to 60 percent by weight. At the time of the conduct of this investigation there was no procedure in Engineer Manual EM 1110-2-1906 for compaction testing of soils containing more than ten percent by weight of particles larger than 1-in. The procedures currently given in Appendix VIA of the manual were derived from this work. Therefore, the method employed in creating the scalped/replaced gradations shown in Figure 29 was identical to that now prescribed. The materials used were a subrounded to subangular concrete mortar sand, a clay (CL), and a subrounded to subangular washed gravel. The gradation and classification data for the sand and clay are shown in Figure 30 For emphasis, it is immediately brought to the attention of the reader that the minus No. 4 fraction of each gradation containing gravel was different and varied from a clayey sand for the 10 percent gravel mix to a sandy clay for the 60 percent gravel material. It was also decided to perform a limited test series on three gradations (see Figure 31) with variable fines (CL) content and their corresponding scalped/replaced gradations.

34. The total quantity of soil required for each test specimen was batched separately. The minus No. 4 material was thoroughly mixed with a predetermined quantity of water, stored in an airtight container and allowed

to cure for at least 16 hr. The gravel for each specimen was prepared by combining the desired air-dry fractions, i.e., 3- to 2-in., 2- to 1.5-in., 1.5- to 1-in., 1-to 3/4-in., 3/4- to 1/2-in., 1/2- to 3/8-in., and 3/8-in. to No. 4, and storing the combined material in containers filled with water. The total gravel fraction was reconstituted from these several size ranges in order to maintain some control over the accuracy of the gradation. Immediately prior to compaction, the cured minus No. 4 fraction was mixed with the saturated surface-dry aggregate. The material required for each layer of the specimen was also batched separately to reduce variation in grading among layers.

35. Table 14 lists data pertinent to the mold sizes, rammer sizes, and the compaction procedures. As in the case of the first Donaghe and Townsend investigation, the hand-held rammer was of the old USACE design and the configuration of the mechanical compactor was such that standard effort could not be precisely applied.

36. The pertinent data resulting from Donaghe and Townsend's second investigation is summarized in Table 15. The findings of this investigation are given in overview as follows:

a. Figure 32 shows the effects of equipment size and procedural differences on compaction curves obtained for the same materials and again indicates that use of a larger mold and commensurate procedures increases the efficiency of the applied energy even for the gradation which contained no gravel. The mechanical compactor was used for both tests in the 6-in. mold and the 18-in. mold. Table 14 shows that the ratio of hammer foot diameter to mold diameter was maintained between the two mold sizes but not the drop height or number of blows per layer. There was no testing done to separate individual effects. It is seen that the maximum dry unit weight obtained in the larger mold was about 4 pcf higher than that obtained in the smaller mold. This approximate magnitude of difference was also reported by Ziegler (1948), Cunny and Strohm (1964) and the South Atlantic USACE Division Laboratory (1968). It is recalled that the USBR in their 1963 report obtained differences between 4-in. mold (hand-held rammer) and 20-in. mold (mechanical compactor) in excess of 9 pcf (see Figure 13).

b. Figure 33 indicates the magnitude of effects on compaction parameters resulting from the scalping/replacement procedure applied to a full-scale material containing 40 percent gravel. Since mold size represents effects of its own, the full-scale gradation and its derived scalped/replaced gradation were both tested in the 18-in. mold so that the only variable was the gradation of the gravel fraction. The scalped/replaced gradation exhibits a distinctly different compaction curve with a maximum dry unit weight 3.9 pcf lower and an optimum water content 1.4 percentage points higher than the corresponding values for the fu.l-scale material. There is a slight shift toward a higher degree of saturation at optimum water content for the scalped and replaced gradation but otherwise the two curves appear to reflect a difference in effective energy as has been previously spoken to.

c. Figure 34 presents the compaction curves obtained on all gradations with a 3-in. maximum particle size and various percentages of gravel. The zero percent gravel gradation was simply the mixture of the sand (SP) and 25 percent by weight of the clay (CL). It does not represent a minus No. 4 fraction since that fraction varied in each of the other gradations as previously pointed out. It is seen that as the gravel content reaches and exceeds 40 percent, the compaction curves begin to deviate from the consistent trend in increasing maximum dry unit weight and decreasing optimum water content exhibited by the gradations with lesser gravel content. The 60 percent gravel content data is significantly different from any of the other curves, particularly with respect to a lower degree of saturation at optimum water content. Whether one chooses to use the bulk or the apparent specific gravity of the gravel, it can be easily shown that the trend in maximum dry unit weight cannot be explained by the trend in weighted specific gravities (Equation 3) of the mixes. On the other hand, as long as the minus No. 4 fraction continues to receive essentially full compactive effort and there are no inordinate voids around or among gravel particles, the addition of gravel results in a dry unit weight increase because the solid particles replace material which would otherwise contain voids, i.e., for a given total volume there is a greater volume of solids. Figure 35 shows that as the gravel content increases so does the maximum dry unit weight in essentially a linear fashion until about 40 percent gravel where it begins to decline as the obvious result of reversal of the increase in volume of solids or, conversely, the increase in volume of voids. The discussion of possible explanations of this occurrence is reserved until after presentation of the findings of the current investigation rep^rt. However, whatever the explanation, Figure 35 shows that the trend in gravel effects is smoothly transitional.

d. Figures 36 and 37 present compaction curves obtained on minus 3/4-in. scalped and replaced gradations corresponding to the full-scale gradations of Figure 34 except for the zero percent gravel gradation. These tests were performed in the 6-in. diam mold using both the mechanical compactor (Fig. 19) and the hand-held rammer (Fig. 30). The maximum dry densities of the scalped/replaced gradations are also plotted in Figure 35 for the purposes of comparison with the full-scale gradation data. Small (considered insignificant) differences were observed among values of maximum dry unit weight and optimum water content obtained by the mechanical compactor and the hand-held rammer. The mechanical compactor yielded maximum densities mostly slightly higher (maximum of 0.7 pcf) than those yielded by the hand-held rammer. The very small differences in optimum water contents appeared to be random in relative direction with respect to equipment type. For these materials, the old version CE hand-held rammer did not mismatch the energy of the mechanical compactor to the degree seen in the previous study for the DeGray Dam gradation. There is no ready explanation of these observations. As has been previously seen for scalped and replaced gradations, the compaction parameters do not match those of the corresponding full-scale gradations. The maximum dry unit weights are lower and the optimum water contents are higher than those of the full-scale gradations. The deviations of maximum dry unit weight of the scalped/replaced gradations from the corresponding full-scale gradations are plotted in Figure 38. The differences occur at even the lowest gravel contents. Furthermore, unlike the full-scale gradations, the scalped and replaced values of maximum dry unit weight appear to decline steadily with increasing gravel content. Since the minus No. 4 fraction was identical between corresponding full-scale and scalped/replaced materials, the source of the difference seen must be the difference in gradation of the gravel fraction.

e. The compaction curves for the minus No. 4 fractions of the full-scale gradations performed in the 4-in. mold with the hand-held rammer are shown in Figure 39. Using these data in companion with that presented above, it is now possible to address the applicability of Equations (1) and (2) in predicting the maximum dry unit weight and optimum water content of the full-scale gradations from tests performed on the minus No. 4 fraction or vice versa. Furthermore, if the scalped/replaced gradations are viewed as just another set of earth-rock mixtures with more uniformly graded gravel fractions, the same comparisons can be made. It is immediately obvious because of the differences in compaction parameters seen between the full-scale and companion scalped/replaced gradations that Equations (1) and (2), if they predict well in either case, certainly cannot do so for both. Figure 40 shows the results of application of Equation (1) between full-scale and corresponding minus No. 4 fractions. Up to a gravel content of 40 percent, Equation (1) closely predicts the maximum dry density of the full-scale material utilizing the maximum dry unit weight of the minus No. 4 fraction and vice versa. However, Figure 41 presenting results of the same computations applied to scalped/replaced data reveals that Equation (1) does not predict maximum dry unit weights in either direction beginning at the very lowest gravel contents. Examining the deviations of maximum dry unit weights of the gradations containing gravel predicted from the minus No. 4 fraction from their actual values, it is seen that the deviation at 50 percent gravel for a full-scale gradation (Fig. 33) is approximately equivalent to that for the a scalped/replaced gradation containing 20 percent gravel (Fig. 34). It is interesting to note from the family of gradation curves of Figure 29 that the gradations of the gravel fractions of these two materials are essentially parallel. This is to say that the gravel gradation of the scalped/replaced material containing 20 percent gravel corresponds with respect to uniformity to that of the full-scale gradation contair :g 50 percent gravel. A very crude computation using an average spherical particle diameter of gravel for these two gradations reveals that the number of average size particles in the scalped and replaced gradation is some 20 times larger than that for the full-scale gradation. This leads to the suggestion that it is not the number of gravel particles which produces an apparent reduction of effective compaction effort which reaches the minus No. 4 fraction but rather the gradation of the gravel.

f. The optimum water content data for all gradations and values predicted using Equation (2) are plotted in Figure 42. No value of absorption was determined for the gravel but its effect on the calculations yielded by Equation (2) is so minor and the range in its value for most aggregate is so confined that the assumption of a value of 4 percent is considered acceptable. It is evident that the water contents predicted from the optimum values of the minus No. 4 fractions fall within one percentage point of the optimum water contents of the full-scale gradations for every gravel content. On the other hand, this is not true for the scalped/replaced gradations except for the lowest gravel content. The water contents of the minus No. 4 fractions predicted from the optimum values of the corresponding full-scale materials generally deviate about one percentage point either side of the actual values of optimum water content of the fraction. It is noted that the deviations of predicted values from observed values is larger for the minus No. 4 fractions than for the full-scale gradations. It is a noteworthy occurrence that the gravel content (40 percent) at which the trend in predicted values of water content intersect and cross over the trend in actual values of optimum water content for both full-scale materials and minus No. 4 fractions corresponds to the gravel content at which the predicted maximum dry unit weight values begin to clearly deviate from actual values (see Figure 40). The relative proximity of predicted values of water content to observed optimum values is interpreted to imply that, whatever the precise effects of the addition of various amounts of gravel, the changes in optimum water content resulting appear to be consistent with the addition of solid particles replacing material containing voids, the comparative efficiency of applied compactive effort on the minus No. 4 material between the 4-in. and 18-in. molds and the "interference" of the gravel on the efficiency of applied energy affecting the minus No. 4 fraction.

g. The testing by Donaghe and Townsend related to the effects of fines content is addressed in Figures 43 through 46. The results with respect to maximum dry unit weight are summarized in Figure 46 where it is seen that fines content did not significantly effect the usefulness of Equation (1) in predicting full-scale maximum dry unit weights from those of the minus No. 4 fractions or vice versa. As before, the scalped/replaced gradations did not model the full-scale results nor could the maximum dry unit weights be predicted with acceptable accuracy with Equation (1) between these gradations and the minus No. 4 fractions. The optimum water content data is given in Figure 47 where these same conclusions apply.

Garga and Madureira (1985)

37. The last work to be summarized is that by Garga and Madureira (1985) who performed a particularly extensive compaction investigation concerning a natural river terrace soil employed in the construction of Sao Simao Dam in Brazil. The soil varied from a well-graded gravelly clayey sand to a clayey sandy gravel. As seen in Figure 48, the coarse fraction content (plus No. 4 fraction) ranged from 30 to 70 percent by weight while the fine fraction (minus No. 200 sieve) ranged from about 10 to 35 percent. The gravel sizes were rounded to subrounded in shape, exhibited an average bulk specific gravity between 2.5 and 2.6 and an absorption between 1 and 3 percent. The Atterberg limits associated with the minus No. 4 fractions were a Liquid Limit range of from 20 to 35 percent and a Plasticity Index of 5 to 15 while the specific gravity of the solids (G_s) varied from 2.76 to 2.87. Nominal mold diameters of 4-in., 6-in., 12-in. and 20-in. were used. The characteristics of the compaction equipment and methods used to achieve the desired compactive efforts are given in Tables 16 and 17, respectively. Because preliminary field compaction trials showed the compacted densities to be close to those obtained using an intermediate energy (24,985 ft-lbs/cu ft), most laboratory tests were performed using this energy. The USBR Earth Manual (1963) Specifications E-11 and E-38 were generally followed.

38. The coarse fraction (gravel, i.e., plus No. 4 sieve sizes), with a maximum size of 3-in. was separated at the No. 4 sieve into 3/8-in., 3/4-in., and 1-1/2-in. sieve sizes. In order to determine the moisture-density curves, five samples with rectilinear gravel fraction grain-size curves were composed for each required gravel content. For example, a sample containing 60 percent gravel with a maximum particle size of 3-in. would contain 15 percent retained on each of the No. 4, 3/8, 3/4, and 1-1/2-in. sieves and 40 percent minus No. 4 material as illustrated in Figure 48. The specimens were batched by adding required amounts of gravel to the minus No. 4 material from a stockpile. Preliminary test results had indicated that relatively small variations in grain size and plasticity of the minus No. 4 materials had a significant effect on the maximum dry unit weight. Thus, the index properties and the

maximum dry unit weight of the minus No. 4 fractions were determined for each series of tests. Compaction tests were not carried out beyond a gravel content of 70 percent, since several previous investigations (Jones 1954; Holtz and Lowitz 1957; Gordon et al. 1959; and Pellegrino 1965) indicated that the highest maximum dry densities of earth-rock mixtures are obtained at gravel contents below 70 percent. Garga and Madureira state that water was added only to the minus No. 4 fractions, with the gravel fraction remaining at its natural water content (between 1 and 3 percent) while in some test series the coarse fraction was saturated and then surface dried (ASTM Method C97) to study the effect of water absorption of the gravel on the compaction characteristics. The two fractions were then mixed and left to cure for at least 12 hr.

39. Before each compaction test, a representative sample oı ·h minus No. 4 material was obtained for determination of its water content. Because of the lack of adequate oven space, the water content of the total material was calculated using Equation (2) from the measured water content of the minus No. 4 fraction and either an assumed water content of the gravel fraction or its absorption. In following this procedure, Garga and Madureira state that the water content of the gravel fraction mixed at its natural water content (1 to 3 percent) was taken as zero while the water content of gravel mixed in a saturated surface-dry state was taken as its absorption (also 1 to 3 percent). The explanation of this practice was that it had no significant effects on results. This will be examined in discussion of findings below. They further state that the dry unit weight of the minus No. 4 fraction within a compacted mixture was back-calculated from the percent gravel, dry unit weight of the compacted total material, and the water content of the minus No. 4 and gravel fractions. The writers can only interpret this to mean that once the dry unit weight of the total sample was calculated using the fraction water contents, Equation (1) was applied to calculate the dry unit weight of the minus No. 4 fraction.

40. The results of the compaction test program are summarized in Table 18. Selected findings by Garga and Madureira were as follows:

- a. Comparative tests (Table 18, Series 7,8,16,18 and 19) were done to determine the effects of mold size on compaction parameters (implicitly also includes effects of rammer sizes and layer thicknesses). Figure 49 presents the results of Test Series 7,8,18 and 19 on minus 3/4-in., minus 1-1/2-in. and minus 3-in. gradations. For the minus 3/4-in. and minus 3-in gradations the maximum dry unit weights obtained in the larger mold tended to be only slightly higher than those obtained in the smaller mold. However, the tests on minus 1-1/2-in. materials showed a reverse trend. The magnitude of the differences are smaller than those observed from the previous studies reviewed. This is true even though for the minus 1.5-in. and minus 3-in. gradations the ratio of mold diameter to maximum particle size was as low as 4 in the small molds. Indeed, considering the typical precision, i.e., repeatability, of compaction data by a single individual, it may be contended that there were no differences seen. It is pointed out that the data seen in Figure 49 for the minus 3-in. gradations may not be comparable (see Table 18, Test Series 7 and 8) because the minus No. 4 fractions between the two mold sizes were not identical, particularly with respect to the specific gravity of solids, i.e., 2.76 versus 2.87.

b. Figures 50 and 51 present the maximum dry unit weight and optimum water content data for the range of gradations tested applying standard (12,375 ft-lb/cu ft), intermediate (24,985 ft-lb/cu ft) and modified (56,250 ft-lb/cu ft) compaction efforts (Table 18, Test Series 1 through 12). It is seen that there were relatively minor differences in maximum dry densities and optimum water contents obtained among the different gradations for each compactive effort above a gravel content of 30 percent. For both maximum dry unit weight and optimum water content, there were generally greater differences among the minus No. 4 fractions (zero gravel content) than the mixtures with gravel. Garga and Madureira state that preliminary testing had clearly indicated that relatively small variations in grain size and plasticity of the minus No. 4 fraction had a significant effect on the maximum dry unit weight of the total materials containing gravel. However, none of the gradations shown in Figures 40 and 41 contained identical minus No. 4 materials. Liquid Limit of the minus No.4 materials ranged from 26 to 30, Plasticity Index ranged from 6 to 10, Specific Gravity of solids ranged from 2.76 to 2.87 and minus No. 200 ranged from 40 to 55 percent. It is important to realize that because Garga and Madureira used rectilinear grain-size distributions for the gravel fractions that the gradation of the gravel fractions of the minus 1-1/2-in. and minus 3/4-in. materials shown in Figures 50 corresponded to those of scalped and replaced gravel fractions compared to the minus 3-in. materials at the same gravel contents. Other investigators and Garga and Madureira (to be discussed below) have consistently shown that "true" scalped/replaced gradations (i.e., containing identical minus No. 4 fractions) yield lower maximum dry unit weights increasingly with increasing gravel content compared to the parent full scale material (see Figure 38). The absence of this trend in Figure 50 implies that the variations in physical characteristics of the minus No. 4 fractions completely masked the expectably significant effects of increasing uniformity of the gravel fraction for gradations containing the same gravel content. No inferences are attempted relative to optimum water content because the effects of scalping and replacing on that parameter as compared to full-scale materials appears to be erratic (for example, see Figure 36).

c. Figure 52 shows the effects on maximum dry unit weight of varying compactive effort and gravel content for gradations containing a maximum particle size of 1-1/2 in. Again, this figure must be viewed in the knowledge that the minus No. 4 materials were not identical. The 30 and 50 percent gravel gradations exhibited a slight increase in maximum dry unit weight from intermediate to modified effort while the 40 and 60 percent gravel gradations showed decreases. However, it is seen that the differences between intermediate effort maximum dry unit weight and modified effort maximum dry unit weight for the gradations containing 40 or more percent gravel were less than 1 lb/cu ft. Therefore, rather than any actual decrease in maximum dry unit weight from intermediate to modified effort, the probable proper interpretation considering test precision is that very little, if any, densification was achieved for these gradations by increasing effort from intermediate to modified. The minus No. 4 fractions reflected increases in maximum dry unit weight almost directly proportional to the relative increase in compactive effort. With gravel present, however, the mixtures exhibited much greater relative densification between standard and intermediate efforts than did the minus No. 4 material but much less above intermediate effort. Thus, it is evident that the presence of gravel, notwithstanding mold size effects, significantly influences the manner in which the material responds to applied energy.

d. A test series (Table 18, Test Series 15) was performed using identical minus No. 4 material to compare results obtained on three minus 3-in. and three minus 1-1/2-in. gradations which were scalped/replaced on the 3/4-in. sieve to those for their parent full-scale gradations. The results of this series are given in Figures 53 and 54. Remembering that the gravel gradations were all rectilinear, it can be shown that scalped/replaced minus 3-in. gradations would have involved substitution for about 20 percent by weight of the total material at 40 percent gravel, about 25 percent at 50 percent gravel, and around 30 percent at 60 percent gravel. Likewise, the minus 1-1/2-in. gradations would have involved substitution for about 13 percent by weight of the full-scale material at 40 percent gravel, 17 percent at 50 percent gravel, and 20 percent at 60 percent gravel. Surprisingly, at the lowest gravel content tested of 40 percent, the full-scale and scalped/replaced gradations all exhibited precisely identical maximum dry densities even though the mold sizes varied (Figure 53). This occurrence appears to have aroused no suspicions as to its general validity over the range of natural gradations and characteristics of minus No.4 materials. Garga and Madureira concluded from this one test series for the purposes of fill compaction control that the substitution method would replicate full-scale maximum densities at gravel contents below 40 percent. Anyway, this test series clearly confirms the effects of increasing uniformity of the gravel gradation on maximum dry unit weight as observed by other investigators since the only variable among these gradations was the gradation of the gravel fraction. This also indicates that for all the other compaction series where the minus No. 4 fractions varied in grain size, plasticity and specific gravity of solids, that effects of variable uniformity of the gravel fractions between tests series were largely or completely masked. These statements are contradictory of Garga and Madureiras' conclusion drawn from Test Series 17, Table 18, which was performed to examine influence of gradation. They concluded that compacted dry unit weight was essentially independent of the shape of the particle distribution curve. However, Test Series 17 did not include scalped and replaced specimens and there is no indication of characteristics of the minus No. 4 materials. In addition, Test Series 17 involved only 50 and 60 percent gravel contents such that the rectilinear gravel gradations would have remained essentially parallel. From Figure 54, Garga and Madureira saw inconsistent trends in optimum water content but not to the degree that Donaghe and Townsend (1975) report in Figure 36.

e. Garga and Madureira report the performance of a laboratory test program in conjunction with test fills to determine a practical and convenient fill compaction control method. They state as follows:

"At San Simao, with an average gravel content of 40-50 percent, both the substitution (scalping and replacing) and the elimination (scalping) methods could be used for compaction control in the field. The first method was utilized up to a gravel content of 40 percent, while elimination of plus 3/4-in. fraction was used for higher gravel contents. Results of field compaction trials (test fills) provided a direct comparison of the degree of compaction provided by the two methods."

The comparative degrees of compaction by the two methods are shown in Figure 55. Garga and Madureira provide no laboratory or field data in support of Figure 55. Table 18 includes no testing of scalped fractions and only one series on scalped/replaced gradations beginning at 40 percent gravel. It is not stated by Garga and Madureira and can, therefore, only be inferred by the reader that they performed comparative scalped and replaced and scalped compaction tests on material extracted from the location of each of the 26 fill density tests corresponding to the data of Figure 55. There is no indication that compaction tests were also performed on the full-scale materials from each density test location. So, it must be presumed that the maximum dry unit weights of the total materials for scalped cases were predicted using Equation (1) and the maximum dry unit weight of the scalped/replaced gradations were taken to be equivalent to those for the total materials. Figure 48 indicates that fill material could have contained anywhere from about 35 to about 75 percent gravel but no information is provided as to the gravel contents of the 26 fill samples. The importance of all of the above presumably omitted information is apparent upon contemplation of Figure 55. That figure indicates that whatever the gravel contents, either scalping/replacing or scalping on the 3/4-in. sieve yielded values of percent compaction which were within two percentage points of each other for each of the 26 data points. The more important, and unanswered question, is which values of percent compaction were more nearly correct? It appears to be an honest question in light of all the effort involving test fills as to why compaction tests were not also performed on the total material from the fill density test locations to establish the true values of percent compaction for comparison to those values yielded by the two "shortcut" methods? Figure 55 also confirms the expected relationship between percent compactions obtained by the two methods used. In the case of use of scalped/replaced gradations to "model" the full-scale material, the maximum dry unit weight yielded for gradations of low gravel content (say, less than 10 percent) would be expected to be close to that of the full-scale parent gradation but would begin to be seriously less than that of the total material as gravel content increases. Therefore, at low gravel content, the substitution method would be expected to provide good estimates of percent compaction but would result in inflated values with respect to correct values as the gravel content increases, i.e., as the percent by weight substituted increases. On the other hand, use of Equation (1) with the maximum dry unit weight obtained on a scalped gradation to predict the full-scale maximum dry unit weight would be expected to slightly underestimate to accurately estimate up to the "interference" gravel content and then overpredict the maximum dry unit weight of the total material above that gravel content. This would result in slightly inflated to "good" values of percent compaction for materials with gravel content less than the interference value but deflated percent compaction for materials with gravel contents above the interference value. So, for 18 of the 26 samples plotted in Figure 55, the substitution method yields a percent compaction which is higher than that obtained using elimination. For the other 8 samples where the opposite was true, it can only be surmised that the gravel contents were sufficiently below the interference values such that the elimination method with Equation (1) yielded higher values compared to the substitution method. None of the above comments are intended to imply that Garga and Madureira did not confirm the adequacy of their selected compaction control procedures.

f. Figures 56 through 60 address the application of Equation (1) in predicting the maximum dry unit weight of a full-scale gradation (minus 3-in. and minus 1-1/2-in.) from that of the minus No. 4 fraction. Since the various maximum particle size and percent gravel gradations were generated by adding gravel to a given minus No. 4 fraction, the dry unit weight of the fine fraction taken into Equation (1) for the range of gravel contents for a given test series is the maximum dry unit weight of that particular minus No. 4 fraction. Figure 61 summarizes the deviations of predicted values from actual values. Figure 62 presents the predicted densities of minus No. 4 fractions in terms of percent compaction. Again, the reader is reminded that the minus No. 4 fractions of all the gradations were variable which tends not only to obscure trends among gradations but also renders comparative observations questionable. Nonetheless, taking a deviation of predicted value from actual of about 2 lb/cu ft as maximum allowable error, it is seen from Figure 61 that Equation (1) would not be dependable for these materials above a gravel content of about 25 percent for standard and intermediate compaction efforts just a Garga and Madureira concluded. At modified compaction effort, the predicted values begin to deviate more strongly from actual values for both the minus 3-in. and minus 1-1/2-in. gradations. This observation raises a serious question as to usefulness of the minus No. 4 fraction for predicting maximum dry unit weight of the total material at modified effort. It was previously pointed out that at the modified effort, the total material showed no significant increase in maximum dry unit weight over intermediate effort while the minus No. 4 material showed a commensurate increase in maximum dry unit weight. Therefore, while the minus No. 4 maximum dry unit weight rose with increased compactive effort, the total material maximum dry unit weight did not which resulted in Equation (1) more severely overpredicting the maximum dry unit weight of the total material. There is no data available to determine how much use of the minus 3/4-in. fraction would have reduced the problem. Figure 62 shows that percent compaction of the minus No. 4 fraction declines steadily as expected with increasing gravel content with the lowest percent compactions associated with modified compaction effort again because of the increase in maximum dry unit weight the minus No. 4 fraction with increase in effort while the total material maximum dry unit weights changed very little.

g. Garga and Madureira did not determine the water contents of total compacted specimens containing gravel but instead calculated those values from water contents obtained on representative samples of the minus No. 4 fraction prior to combination with the gravel and a water content of the gravel of either zero or the absorption. In the cases where the gravel was used at its natural water content (stated to be between 1 and 3 percent), a value of zero was used along with the water content of the minus No.4 fraction to compute the total mix water content. This practice was stated to have insignificant impact on results. But, if the natural water content of the gravel was 3 percent and the gravel content of the mix was 70 percent, Equation (2) indicates an error of 2.1 percentage points. Considering the fact that the optimum water contents of minus 3-in. gradations containing 70 percent gravel were only about 5 percent, this error cannot be treated as insignificant. The issue is brought into clearer focus if fill compaction control is addressed where typical specified range in placement water content for such materials would be on the order of plus or minus 1-1/2 to 2 percentage points with respect to optimum water content. Obviously, inattentiveness to the actual water content of the gravel would result in failure to actually control placement water content as specified. In the cases where gravel was used in a saturated surface-dry condition, an absorption was used in the calculations of total sample water content. The preliminary water contents of the minus No. 4 fractions and the calculated total compacted specimen water contents were reported for these 10 test series. These values were substituted in Equation (2) to back-calculate a water content of the gravel. Figures 63 through 65 provide the results of these back-calculations for the various maximum particle size gradations and various compactive efforts. Nine of the 10 test series employed gravel with a bulk specific gravity of 2.59 and the tenth was 2.56. Garga and Madureira stated that a bulk specific gravity of 2.59 was associated with an absorption of 1 percent while a gravity of 2.56 was associated with an absorption of 3 percent. The one mix with gravel of 2.56 bulk specific gravity was the minus 1-1/2-in. gravel compacted at modified effort (Test Series 10, Figure 64). It is seen from Figures 63 through 65 that the back-calculated gravel water contents tended to average about the stated absorptions but it is clear that specific values of one or three percent absorption would not yield the total sample water contents reported. Test series 12, Figure 63 and Test Series 4, Figure 65 did not conform at all. The minus 3/4-in. gravel of Test Series 4 was almost dry and the minus 3-in. gravel of Test Series 12 exhibited an absorption of 3 percent instead of one percent corresponding to its stated bulk specific gravity of 2.59. Because of this, assessment of the use of Equation (2) to predict optimum water content of the total material from that of the minus No. 4 fraction is not feasible.

41. The authors have summarized the findings of five previous investigations in order to orient the reader regarding the range and effects of variables involved in the determination of compaction characteristics of soils containing large particles. If the reader at this point is somewhat confused, let it be said that the authors also intended to reveal the state of confusion within the profession concerning the subject. However, careful reconsideration of the five studies indicates that the first four (USBR, CDWR and CE) were mutually supportive in several observed trends such as those resulting from the effects of mold size, maximum particle size, gradation of the gravel fraction, etc., while the fifth (Garga and Madureira) indicated very few significant differences among compaction parameters obtained across the range of maximum particle sizes and gradations other than those attributable to

different compactive effort. It was concluded by the authors of this report that the key to the apparent insensitivity of the Sao Simao Dam earth-rock materials resulted from the failure to isolate the characteristics of the minus No. 4 fraction as a test variable. That is to say, Garga and Madureira did not report tests on true scalped gradations and performed only a very limited test series on true scalped/replaced gradations. The test series on true scalped and replaced materials confirmed the trends for such altered mixtures seen by other investigators. The comparisons of compaction data for gradations containing different maximum particle sizes also suffered from the fact that each such gradation contained a different minus No. 4 material. These differences prevent adequate assessment in a research context of effects of gradation of gravel fractions. On the other hand, Garga and Madureira's practice of adding various percentages of gravel to a given minus No. 4 material did provide useful data from each of those separate test series for examining the usefulness of Equations (1) and (2) for predicting full-scale compaction parameters from those of the minus No. 4 fraction at different compactive efforts. It was also valuable to see that a doubling of effort from intermediate to modified resulted in no significant change in the compacted nature of the material across the range of all the variables. In addition, it was of value to learn from Garga and Madureira that the vibratory rollers employed produced compacted densities equivalent to those corresponding to a laboratory effort between standard and modified efforts.

PART IV: TESTING PROGRAM

Testing Objectives

42. The authors had to make decisions concerning a test plan which would conform to funding and time constraints but at the same time produce enough of the right types of compaction data to resolve or significantly contribute to resolving several important issues regarding the laboratory determination of compaction characteristics of earth-rock mixtures. In addition, the test plan was also required to yield data which could be used to assess the quality of current laboratory and field practices related to compaction control. Those practices have been derived or simply adopted as a means of avoiding to a maximum possible degree the laborious, expensive and time-consuming laboratory testing of the natural gradations containing significant percentages of particle sizes dictating large specimens, large-scale testing equipment, and large-scale material handling and processing capabilities. The authors decided upon the following objectives:

a. Development of a large-scale compaction test employing a mechanical compactor, including a suitable range in mold sizes, permitting testing of gradations containing particles up to the 3-in. sieve size and satisfactorily devoid of mold size effects. Selected mold sizes included 6-in., 12-in., and 18 in. diam.

b. Assessment of the adequacy of current practice of EM 1110-2-1906 which allows scalping of an earth-rock mixture containing up to 5 percent by weight of oversized particles to avoid testing in the next larger diameter mold.

c. Assessment of the reliability of equations cited in Appendix B of EM 1110-2-1911 for predicting the maximum dry unit weight and optimum water content of an earth-rock gradation from those of its minus 3/4-in. and minus No.4 sieve fractions.

d. Assessment of the reliability of methods used by other agencies for predicting the maximum dry unit weight of an earth-rock gradation from that of the minus No. 4 sieve fraction.

e. Improvement of the understanding of the effects of gravel content on the compacted state of a fraction.

f. Development of a more reliable method for predicting the maximum dry unit weight and optimum water content of an earth-rock gradation from the corresponding value for the minus 3/4-in. and minus No. 4 sieve fractions.

Test Gradations

43. The most fundamental decision concerns the gradations to be tested. The last research work at WES on compaction characteristics of earth-rock mixtures was that by Donaghe and Townsend (1975). Their primary objectives were to assess the use of the equations for predicting maximum dry unit weight and optimum water content of the total material form those values for a fraction (EM 1110-2-1911, Appendix B) and to evaluate the practice of scalping with replacement. To do so, they generated artificially blended minus 3-in. full-scale gradations (see Figure 29) by fixing the percent fines (minus 200 sieve) at 25 percent, varying the gravel content and adding the dictated sand fractions. The minus No. 200 sieve material was a clay (CL). Therefore, each minus 3-in. full-scale gradation contained a different minus No. 4 fraction with respect to the relative proportions of sand and clay of which it was composed. Consequently, the plasticity of the minus No. 4 fraction increased as the gravel content increased. This was true because the sand content of the minus No. 4 fraction decreased as gravel content increased while the clay content (minus No. 200 sieve fraction) remained constant. Minus 3/4-in. scalped/replaced gradations corresponding to each full-scale minus 3-in. material were tested along with each minus No. 4 fraction. Therefore, the only scalped gradations tested were tne minus No. 4 fractions.

44. To complement the gradational array tested by Donaghe and Townsend, and to address the effects of scalping, it was decided to generate artificially blended gradations predicated upon scalping down in particle size from a maximum size of 3 in. Since it was also desired to achieve a general assessment of the use of various equations for predicting maximum dry unit weight and optimum water content from corresponding values of a fraction, it was also necessary to vary gravel content and plasticity of fines (minus No. 200 sieve sizes). The test program thus included four minus 3-in. full-scale gradations containing 28 to 64 percent gravel with plastic and nonplastic fines and scalped fractions of each of those full-scale gradations having 2 in., 3/4-in. and No. 4 sieve maximum particle sizes. Two minus 3/4-in. (and, consequently, two minus No. 4 fractions) were selected to be added to the various plus 3/4-in. fractions. Note that the scalping approach also resulted in variable percent fines.

45. The gradation curves generated are described in Table 19 and plotted in Figures 66 and 67. Note that each scalped gradation can in itself be treated as a full-scale gradation with a smaller maximum particle size and the next smaller maximum particle size scalped gradation is also a fraction of it. So, compaction test results from each set of gradations with a given maximum particle size can be compared among themselves in like manner. The gradations adopted are typical of those seen in USACE projects in their range, shapes and fines content.

Test Plan

46. The test plan consisted of two phases as follows:

a. Phase I: Develop a large-scale compaction test employing a mechanical compactor, including a suitable range in mold sizes, permitting testing of gradations containing particles up to the 3-in. sieve size and satisfactorily devoid of mold size effects. Selected mold sizes included 6-in., 12-in., and 18 in. diam.

b. Phase II: Using the compaction test procedures developed in a. above, perform standard effort compaction tests on the gradations described in Table 19 and shown in Figures 66 and 67.

The specifics of the Phase I testing to development the large-scale compaction test are presented in Part V of this report.

Testing Techniques

47. Another fundamental aspect of the test program is the decision as to how to approach methods or procedures. Donaghe and Townsend worked within a research context without emphasis on the practicality of their testing technique for routine use by typical USACE Division and field laboratories. For instance, they determined material quantities required for a given compacted specimen such that the last compacted lift overfilled the mold into its collar by about 1/4-in. The unaltered surface of the specimen was then varnished to seal it and the total specimen volume calculated by deducting the volume of water required to fill the space above the specimen surface to the top of the mold collar from the known total volume of the mold-collar assembly. Obviously, such a procedure is not practical for routine testing. Since a major objective of the work reported herein is to develop routine laboratory

compaction test methods, it becomes a necessary imposition upon the study of the effects of the variables that methods and procedures used are of a practical nature as opposed to specialized research techniques and that the tests be conducted by a journeyman level laboratory technician. This approach cannot be said to introduce error because the accuracy of a compaction test is undefined, but there is every reason to expect an impact on testing precision, i.e, the range in results of replicate tests.

Materials

48. The materials tested in this investigation were prepared by combining rounded to angular washed gravel and a subrounded to subangular mortar sand (SP) with either a silt (ML) or clay (CH) to produce the gradations described in Table 19 and plotted in Figures 66 and 67. Classification data for the clay, silt and sand are given in Figure 68. The silt is Vicksburg loess and the clay is commonly referred to as Vicksburg "buckshot" clay. The majority of the gravel particles were subrounded with occasional angular shapes occurring as broken fragments. The placer (alluvial) gravel was obtained from deposits of the American River, California, in the vicinity of the Folsom Dam (near Sacramento). These quartzitic, granitic and andesitic (hard, durable) gravels occur in the foundation of the auxiliary dam and were employed in the construction of the embankments. The bulk, G_m, and apparent, G_a, specific gravities of the gravel were 2.68 and 2.83, respectively, and the absorption (ASTM 1991e) was therefore 2.0 percent [the absorption, $A = (G_a - G_m)/G_aG_m \times 100$ percent].

49. Gradations of the gravel and plus 3/4-in. fractions associated with the gradations of Figures 66 and 67 are given in Figures 69 through 72. Prior to use in the testing program, the three finer components (sand, silt and clay) were spread on a concrete floor and air-dried. After drying, the silt and clay were processed through a corn crusher to break down any aggregations. The washed gravel was also air-dried (air dry water content = 0.6 percent) before sieving into the following size ranges:

a. Plus 3-in. (discarded).

b. 3- to 2-in.

c. 2- to 1-1/2-in.

d. 1-1/2- to 1-in.

e. 1- to 3/4-in.

f. 3/4- to 1/2-in.

g. 1/2- to 3/8-in.

h. 3/8-in. to No. 4 sieve.

Photographs of the utilized size range fractions are shown in Figures 73 through 79.

PART V: PHASE I TESTING PROGRAM: DEVELOPMENT OF THE LARGE-SCALE COMPACTION TEST

The Need

50. Donaghe and Townsend (1973 and 1975) and other previous investigators have indicated that compaction test results for minus No. 4 sieve size materials tested in the 4-in. diam mold will not be satisfactorily replicated molds larger than 6-in. There was no information as to whether or not this same problem could be expected among mold sizes used for gravelly soils, i.e., the 6-, 12- and 18-in. diam molds. Therefore, before conducting the compaction tests on the gradations shown in Figures 66 and 67, it was considered necessary to attempt development of test procedures for gravelly soils which minimized equipment size effects. The achievement of this objective would allow comparative analyses which would lend insight into the impact of equipment and mold size effects on fill compaction control where all control testing is performed in the 4- or 6-in. diam mold. In addition, it was desirable to develop a large-scale compaction test utilizing a mechanical compactor and suitable for use with material containing up to a 3-in. maximum particle size to replace the unpopular and cumbersome 12-in. mold (maximum particle size of 2-in.) and hand-held rammer test currently cited in EM 1110-2-1906, Appendix VIA.

Phase I Testing Plan

51. The objective of Phase I was to develop large-scale compaction test procedures for gravelly soils which were acceptably free of equipment size effects, i.e., acceptably precise. The smallest standard mold size involved in the testing of soils containing gravel is the 6-in. diam mold. Therefore, the results of standard effort compaction tests obtained in that size mold using the mechanical compactor were adopted as the standard of comparison in determining the adequacy of test procedures employing 12- and 18-in. diam molds. Obviously, the test materials were then limited to a maximum particle size of 3/4-in. (sieve size). The authors were of the opinion that a satisfactory test procedure for gravelly soils would not likely replicate results for minus No. 4 material obtained in the standard 4-in. or 6-in. diam mold. So, it was decided to use minus 3/4-in. test materials, i.e., to confine the

objective to gravelly soils only. It was further decided to utilize only the mechanical means of compaction. However, it was planned to test minus No. 4 material in the 6-, 12-, and 18-in. diam molds using the newly developed procedures just to document any differences.

52. Contemplation of a plan of testing to identify compaction test procedures which would replicate results obtained in the 6-in. diam mold with a reasonable precision in the 12- and 18-in. diam molds raised the concern that no single procedure would suffice for all three mold sizes. The possibility of having to vary the number of layers, blows per layer, and hammer weights for some fixed hammer drop height was a fearful one. The decision was made to first perform tests on the selected minus 3/4-in. materials in the 12-in. diam mold employing the same basic procedures as currently used for 4- and 6-in. mold tests in EM 1110-2-1906, Appendix VI, and then try alternative procedures for the 18-in. mold if required. Use of the basic procedures entailed a hammer foot diameter to mold diameter ratio of 1/3, three layers per specimen, equal blows per layer to the extent possible to achieve standard effort for a given hammer weight used in all three molds, and a fixed height of hammer drop of 12-in. Hammer weight was a variable.

Phase I Test Materials

53. The minus 3/4-in. materials used in the Phase I testing were the minus 3/4-in. fractions shown in Figures 66 and 67 and described in Table 19. These are listed in Table 19 as gradations 1B and 3B. A total of four materials were tested since each of the two gradations were tested containing both clay (CH) and silt (ML) minus No. 200 sieve fractions.

Test Equipment

Mechanical compactor

54. The testing was performed using a Howard Model H mechanical soil compactor manufactured by Howard Engineering Company Inc. and mounted on a 30-in. high concrete base. A photograph of the compactor is shown in Figure 80. The compactor is designed for hammers weighing from 5.5 to approximately 100-lb and provides for easily adjustable drop heights ranging from 12 to 24 in. The drop height is self-compensating for heights of soil layers in

the mold. Hammers are picked up by grippers attached to a sprocket chain assembly (see Fig. 80) and dropped when upward movement of the chain brings the gripper holders into contact with the ends of breaker rods hanging from weights supported by the top of the compactor. The grippers are forced back into contact with the hammer when the holders strike reaction posts on a cross member of the compactor at the bottom of the following downward stroke of chain travel. A variable speed motor drive furnished with the compactor can be used to eliminate the tendency to "throw" heavier hammers by slowing the rate of chain movement. The drive allows for blow rates ranging from approximately 12 to 30 blows per minute. Controls include an automatic pre-determining reset type counter which can be adjusted to apply the required number of blows and stop the machine at the end of the pre-set number of blows. A control box with a "Jog", "Run" and "Stop" switch provides a means of starting a cycle of blows, stopping during the cycle, jogging to clear the hammer from the mold during the cycle, restarting operation during the cycle and jogging to clear the hammer from the mold at the end of the cycle. The compactor can be used with molds ranging from 4 to 18 in. in diameter. Molds are attached to a turntable on the base of the compactor which provides for manual control of rotational and forward and backward movement of the molds so soil layers can receive both peripheral and central blows.

Hammers

55. The hammers are pictured in Figure 81 and summarized in Table 20. The hammer used for the 6-in. diameter mold test had a 2-in. face diameter, weighed 5.5 lb and was fabricated from 2-in. O.D. metal tubing. Different diameter feet could be attached to this basic hammer along with the addition of lead weights permitting variation of hammer weight. Hammers used in the 12-in. diam mold tests had a face diameter of 4-in. and weighed 38.4, 58.8 and 78.8-lb. These weights could be conveniently produced with combinations of available lead billets added to the basic 5.5 lb hammer after addition of the 4-in. diam foot. The hammer weight of 58.8-lb conveniently produced in this manner also allowed 56 blows per layer to approximately achieve standard compactive effort to match the blows per layer of the standard 6-in. diam mold test. The additional hammer weights of 38.4 and 78.8-lb were chosen to provide sufficient variation in hammer weight to determine relationships between hammer weight and compaction characteristics while maintaining approximately

equal number of blows per layer in achieving approximate standard effort. The total energies delivered by these hammer weights are also shown in Table 20.

56. The use of hammers having face diameters 1/3 that of the mold require both peripheral and central blows for complete coverage of layer surfaces. The Howard compactor allows central blows to be achieved by sliding the mold backward or forward so the hammer can strike the central portion of the layer. However, most mechanical compactors do not allow for lateral movement of the hammer. Therefore, in addition to the 12-in. diameter mold tests employing a hammer face diameter of 4-in. and the weights stated above, a 131.4-lb hammer with a 6-in. diameter face designed for use with the 18-in. diam mold was also used both to determine effects of using a heavier hammer and to employ a hammer which would not require the mold to be moved laterally in order to apply blows to the central portion of each layer. The 131.4-lb hammer weight for the 18-in. diameter mold corresponded to 25 blows per layer (same as for the 5.5-lb hammer in the 6-in. mold) to achieve approximate standard compactive effort. During the conduct of Phase I testing, breaker rods and guides furnished with the compactor were found to not be substantial enough to perform tests using the 131.4 lb hammer and were replaced with the 1-in. diameter rods and linear ball bushings shown in Figure 82.

Molds

57. The molds are also shown in Figure 81 and had the dimensions and volumes given in Table 20. These molds were equipped with 2-in. high collars and were attached to the turntable on the base of the compactor with bolts and ear type clamps. The 18-in. diameter mold was split and hinged on one side to facilitate removal of specimens after testing. An additional 4-in. high tin collar was used with the 18-in. diameter mold to allow placement of all of the material for the last layer prior to compaction.

Obtaining compacted specimen weights

58. A special harness for suspending the 12 and 18-in. diam molds from a forklift was rigged with an electronic load cell sensitive to within 0.1-lb to obtain specimen-plus-mold weights. A photograph of the harness with the 12-in. diameter mold is shown in Figure 83. After specimen plus mold weights were obtained, the specimens were placed in pans and weighed again using platform scales accurate to 0.1-lb. Weights of specimens obtained from 6-in. diam mold tests were obtained using a digital scale accurate to one gram.

Specimen Preparation

59. Batches for test specimens were prepared by first thoroughly hand mixing predetermined amounts of air-dry silt or clay and sand with measured quantities of water in a large pan. The combined finer material was then pushed through 1/4-in. hardware cloth and placed in sealed containers to cure for at least 16 hr prior to testing. The gravel for each batch was prepared by combining predetermined weights of each air-dry (water content = 0.6 percent) size range and adding the gravel to the desired wet weight of cured minus No. 4 material immediately prior to compaction. Each layer was batched separately to maintain gradation between layers. Total batch weights were computed assuming dry densities 5 to 10 lb/cu ft greater than the estimated maximum dry unit weight for each gradation to provide sufficient material to adjust layer heights and assure that the compacted specimen would extend approximately 1/4-in. into the mold collar and to achieve approximately equal volume layers. Photographs taken during batching of a full scale material containing silt fines are given in Figures 84 through 89.

Compaction Procedures

60. Table 20 lists data for hammer sizes and compaction procedures used for the various molds. All specimens were compacted in 3 layers maintaining standard effort (12,375 ft-lb/cu ft) as closely as practicable by adjusting the number of blows for each hammer used. All tests were performed using a hammer drop height of 12 in. The total energies applied for each test procedure are also given in Table 20. It is seen from Table 20 that the total energies varied to some degree but the maximum variation from standard effort (12,375 ft-lb/ft^3) was less than two percent. It is to be noted that the procedures for standard effort tests in the 4- and 6-in. diam molds given in EM 1110-1906 and in ASTM method D 698 do not precisely match each other in total energy applied. Peripheral blows were evenly spaced and delivered so that the hammer foot struck within approximately 0.1-in. of the side wall of the mold. Central blows were also evenly spaced and were delivered along a circular path at one-half the radius of the mold. Material for each layer was placed in the mold and tamped lightly by hand prior to compaction so the hammer would not produce deep imprints into which significant amounts of

surrounding material could fall during the application of initial blows. Following application of the required number of blows for the first and second layers, the distance from the top of the collar to the respective layer surfaces was measured at several locations as shown in Figure 90 to determine if layer heights were approximately correct. If layer heights were not within approximately 0.1-in. of the desired height (one third of the height of the mold and 0.25-in. of material extending into the collar), the amount of material added for the next layer was adjusted relative to that previously used to achieve the desired height for the next layer. Figure 91 shows the top of the last layer of an 18-in. diam mold specimen following completion of hand tamping and prior to compaction. Figure 92 shows the same specimen after completion of compaction. A ball point pen is shown on the surface of the specimen to give an indication of size.

61. After the last layer was compacted, the collar was removed and the top of the specimen was trimmed flush with the top of the mold. Large particles at the surface of the specimen were either removed or hammered below the top of the mold. Voids remaining after removal of large particles were patched with material remaining from layer batches. Figure 93 shows the top of an 18-in. diam specimen following trimming and patching. After trimming and patching, a lifting yoke was placed on the 12- and 18-in. diam molds and they were moved from the compactor to a large pan where the load cell harness was attached to the yoke and the specimen plus mold weight was obtained to determine the specimen wet weight. Figure 94 shows an 18-in. diam mold and specimen suspended from the lifting yoke over the pan prior to lowering the mold into the pan and attaching the load cell harness. After obtaining the specimen wet weight using the load cell, the specimen was removed from the mold and placed in the pan. A photograph of a specimen after removal from the mold is shown in Figure 95. The specimen plus pan weight was then obtained using a 1000-lb capacity industrial scale to provide a backup check of the specimen wet weight. The pan containing the specimen was then placed in a large oven where the total specimen was dried to obtain the specimen dry weight and water content. Post test handling of specimens for 6-in. diam mold tests was according to procedures given in EM 1110-2-1906.

Results of 12-in. Diameter Mold Tests

62. Results of tests performed on the minus 3/4-in. fractions described in Table 19 containing both clay (CH) and silt (ML) fines to develop a standard effort test procedure for a 12-in. diam mold in which equipment size effects are minimized are given in Tables 21 through 24 and presented graphically in Figures 96 through 103. A summary of optimum water contents and maximum dry unit weights determined from the tests is given in Table 25.

63. Plots of maximum dry unit weight and optimum water content versus hammer weights for the 6 and 12-in. diameter mold tests given in Figures 96 through 103 surprisingly indicate only small differences in results for the 12-in. diameter mold results compared to those obtained with the 6-in. mold. Including all four test series, optimum water content values ranged from 0.6 percentage points less to 0.2 percentage points greater and maximum dry unit weight values ranged from 2.2 pcf less to 2.9 pcf greater than the corresponding 6-in. diam mold values. Table 25 also presents the precision of each test series expressed in terms as previously discussed in Part II. It is seen from that table that the ranges in optimum water content were all less than 10 percent of the average value and all but one of the ranges in maximum dry densities were less than 2 percent of the average. The deviant case was for Gradation No. 3B containing clay (CH) fines where the range in results was 2.5 percent of the average value. Therefore, the authors conclude that results achieved between the two mold sizes and over the range of hammer weights warrant the statement that differences within the expected range of precision of the test were seen between the tests performed in the 12-in. mold using various hammer weights and the tests performed after EM 1110-2-1906 in the 6-in. diam mold.

64. Because of the small differences in results using different hammer weights and because lateral movement of the mold could be eliminated through use of a 6-in. diameter face hammer, it was decided to adopt the 131.4-lb hammer for the standard test procedure for the 12-in. diameter mold. Figures 100 and 101 show that this hammer best reproduced the 6-in. mold results for both maximum dry unit weight and optimum water content.

Results of 18-in. Diameter Mold Tests

65. In order to determine whether the 131.4-lb hammer could also be used for the 18-in. diam mold, a series tests was performed using that hammer on the same materials tested in the 6 and 12-in. diam molds. Results of these tests are given in Table 26 and are shown graphically along with those for the 6 and 12-in. diam mold tests in Figures 104 through 107. Shapes of the compaction curves for the 18-in. diam mold tests shown in these figures are not significantly different than those for the 6-in. diam mold tests. For all four gradations tested, the maximum variation in maximum dry unit weight and optimum water content between the 6 and 18-in. diam mold results was only 0.5 pcf and 0.5%, respectively, (see Table 27) and fell well within two percent precision for a single operator. These variations were smaller than those obtained for the 131.4-lb hammer with the 12-in. diam mold.

66. Plots of maximum dry unit weight and optimum water content versus mold diameter for the 6-in. diam mold tests (5.5-lb hammer) and 12 and 18-in. diam mold tests (131.4-lb hammer) given in Figures 108 and 109 are graphical summaries of data given in Table 27. The small variations of results with mold size indicated by these plots show that use of the 6-in. diam face, 131.4 lb hammer provided a satisfactory means of minimizing (but not eliminating) equipment size effects for 12 and 18-in. diam mold tests performed on minus 3/4-in. gradations within the range of gravel content and plasticity of fines tested. However, use of the 6-in. diam hammer with the 18-in. diam mold reinstates the need for lateral movement of the mold to apply blows to the central portion of each layer. It was decided that a requirement for mold mounts permitting lateral movement was the better approach compared to undertaking a test series to determine acceptability of a 9-in. diam hammer for the 18-in. mold. This decision was also justified by the fact that a once-for-all provision for moveable mold mounts was preferable to swapping of hammer face diameters between the 12- and 18-in. diam molds which requires a troublesome disassembly of the compactor.

Recommended Compaction Test Procedure

67. In summary, compaction test procedures differing only in blows per layer for the 12- and 18-in. diam molds were found to satisfactorily replicate

the results of tests performed in the 6-in. diam mold on minus 3/4-in. materials containing 10 and 40 percent gravel and both clay (CH) and silt (ML) fines. Those procedures employ a 131.4 lb hammer with a 6-in. diam foot. The recommended procedures are given in Appendix A.

Compaction of Minus No.4 Material Using 12 and 18-in. Diameter Mold Procedures

68. After establishing that the procedures using the 131.4-lb hammer would satisfactorily match results of 6-in. diameter mold tests in the 12 and 18-in. diam molds for the minus 3/4-in. fractions, it was decided to see how results among 6, 12 and 18-in. molds would compare for a material containing no gravel, i.e., minus No. 4 fractions. Data resulting from these tests are given in Tables 28 and 29 and plotted in Figures 110 through 115. Table 29 also includes precision parameters which reveal a distinct difference between the consistency of results for the gradations with silt fines as opposed to those with plastic clay fines. Results obtained in the larger molds for the soils containing plastic fines did not compare as well to those obtained in the 6-in. mold as did the results in the larger molds for the soils containing the silt fines. Also, for both plastic and nonplastic fines, the larger molds yielded higher maximum dry unit weights and lower optimum water contents. There was consistency among the data in the sense that whenever the maximum unit weight was higher for one mold compared to another, the optimum water content was at least equal but usually lower. However, Figure 116 shows the trends in these values by mold size to be inconsistent and the so-called "lines of optimums" are curvilinear in opposite directions depending upon plasticity of fines. It is concluded that the 12 and 18-in. diam mold procedure cannot be trusted for use with soils containing no gravel. Considering the mixed trends of Figure 116, there may be no way to develop one procedure for minus No. 4 materials in large molds which would be suitable over a wide range of material plasticity.

69. Parenthetically, as a matter of academic interest with respect to mold size effects, the minus No. 4 fractions, i.e., gradation Nos. 1C and 3C with both silt and clay fines were also compacted in the 4-in. diam mold using the procedure of EM 1110-2-1906, Appendix VI, i.e., the 5.5 lb hand-rammer. Figure 117 presents the maximum dry unit weights and optimum water contents

from those tests plotted with the same parameters obtained in the 6-in. diam mold with the mechanical compactor(see Table 29). Table 30 presents the discrete data for these tests and Table 31 shows the maximum dry unit weights and optimum water contents. Except for gradation 3C with clay fines, Figure 117 shows that the results from the two mold diameters for the minus No. 4 materials fell within the precision ranges of two percent of mean value for maximum dry unit weight and ten percent of mean value for optimum water content. It is noted that gradation 3C is a sandy clay with 58.3 percent passing the No. 200 sieve. Gradation 1C is a clayey sand with 38.9 percent fines. It isn't really surprising that the sandy clay (CH) gradation 3C proved to be the mismatch between the two molds with respect to precision since it is often difficult to clearly define the compaction parameters of a fat clay with no variation in mold size. The differences seen between the 4 and 6-in. diam molds with respect to maximum dry unit weight for gradation 3C with clay fines should probably not be considered significant in the absence of replicate tests.

Phase II Testing Program

70. As was discussed in Part IV, the Phase II testing program was to perform standard effort compaction tests on the gradations described in Table 19 and shown graphically in Figures 66 and 67. The procedures used were those determined from the Phase I testing program as discussed above and described in Appendix A.

PART VI: DISCUSSION OF RESULTS OF THE PHASE II TESTING PROGRAM

General

71. Before entering a discussion of the results of the Phase II testing program and subsequent usage of the data for studying the effects of added gravel, it is important to state another rationale adhered to by the authors. The compaction curves fitted to all compaction data represent the fundamental basis of all that follows in this report. Values of maximum dry unit weight and optimum water content are subjective judgments of the individual fitting the compaction curve to data usually exhibiting some scatter. This is obviously a part of the precision question. The relative effect of judgment is greatest for optimum water content simply because the numerical value of that parameter is only on the order of 5 to 8 percent for earth-rock mixtures. The very first order of business in preparing this report was to fit compaction curves to the test data for every gradation and select the values of maximum dry unit weight and optimum water content. This was accomplished by a very experienced senior engineering technician. Thereafter, the fitted curves and corresponding maximum dry unit weights and optimum water contents were "cast in stone" and not altered in any manner to improve any apparent trends (as could have easily been done). The authors adopted this approach in the belief that any findings must reflect conventional "good" practice within the context of CE division and field laboratories. This is particularly true for any findings relative to adequacy of any "shortcut" methods such as use of equations to correct results of tests performed on a fraction to predict the parameters for the full-scale material.

Effects of Successive Scalping

72. Compaction tests performed on the four minus 3-in. full-scale materials using the 18-in. diam mold and their minus 2-in. fractions using the 12-in. diam mold permits the examination of the effects of successive scalping of materials having a maximum particle size of 3-in. in which the percentage by weight of plus 3/4-in. material and plasticity of fines was varied. These tests combined with those on minus 3/4 and No. 4 sieve fractions, make up a suite of tests performed on gradations representing scalping of the minus

3-in. full-scale gradations on the 2-in., 3/4-in. and No. 4 sieves. It was hoped these tests could be used to provide an idea of the extent to which materials could be scalped and tested with smaller molds to provide results representing nonscalped material compaction characteristics. The reader is reminded that the test gradations are given in Figures 66 and 67. Figures 118 through 121 show compaction curves along with optimum water content and maximum dry unit weight values determined for the gradations with silt (ML) fines and Figures 122 through 125 provide the same information for the gradations with clay (CH) fines. Corresponding test data summaries are given in Tables 32 through 35 and Tables 36 through 39, respectively. Table 40 summarizes the values of maximum dry unit weights and optimum water contents obtained from the discrete data of Tables 32 through 39.

Maximum dry unit weight

73. Relationships between maximum dry unit weight and maximum particle size for full-scale and scalped gradations having nonplastic and plastic fines are shown in Figures 126 and 127, respectively. The curves of these figures give an idea of how scalping (or conversely, the addition of larger particles) affects maximum dry unit weights. Except for gradations formed from minus 3/4-in. materials having 40% gravel (Gradations 3 and 4, Figure 127) with plastic (CH) fines, the curves show that maximum dry unit weights for scalped materials are reduced at increasingly greater rates as maximum particle sizes are decreased. In the case of gradations formed from minus 3/4-in. materials having 40% gravel (Gradations 3 and 4, Figure 127) and CH fines, the same trend is seen below a maximum particle size of 2-in. but a slight increase in maximum dry unit weight was obtained for minus 2-in. fractions as compared to full-scale (3-in. max.) materials. This slight increase in maximum dry unit weight for the CH fines materials may possibly reflect effects due to the different mold sizes (18-in. for minus 3-in. material and 12-in. for minus 2-in. sizes) used to perform the tests. It is recalled that the "standard" procedure developed for the 12-in. diam mold produced a slightly higher maximum dry unit weight for the minus 3/4-in. materials containing plastic fines compared to that obtained on the same material when tested in 18-in. diam mold (see paragraph 63). However, there are other factors to be considered as discussed below.

74. Figures 126 and 127 can also be employed to imply effects of oversize material on maximum dry unit weight. The trends are not only reflective

of gravel content but also include influence of quantity of fines and their plasticity. If the data are segregated into two bands according to the gradations with identical minus 3/4-in. fractions, i.e, Gradations 1 and 2 paired and 3 and 4 paired, a general impression of the effects of increasing gravel content can be seen. The trends are more clearly evident in Figures 128 and 129 where the maximum dry densities for the two pairs of gradations are specifically plotted against gravel content. These four figures taken together help to separate and clarify the gravel content versus mold size effects.

a. Non-plastic fines. It was previously pointed out in the discussions of past investigations that given a particular minus No. 4 material, the addition of increasing quantities of gravel results in increasing maximum dry unit weight up to some "optimum" gravel content in excess of which the trend reverses and maximum dry unit weight decreases. The flattening of the slope of the bands in Figure 126 with increasing maximum particle size seems to suggest the approach of "optimum" gravel content and Figure 128 supports that concept when the same data is plotted in terms of gravel content. Furthermore, the differences in maximum dry unit weight for Minus 3-in. and Minus 2-in. gradations appear much less significant than in Figure 126 so that the authors choose to emphasize gravel content as the predominant variable in Figure 128 and draw on trend curve through the data sets. Of particular interest for the gradations containing silt fines is that the shaded bandwidths in Figure 126 overlap at a maximum particle size of 3-in. The bandwidth at this point indicates an increase in maximum dry unit weight of approximately 3 pcf for the 3-in. maximum particle size materials obtained by increasing the plus 3/4-in. material from 20 to 40%. The fact that the shaded areas appear to merge and coincide at a maximum particle size of 3-in. indicates that compaction characteristics of silty materials having a maximum particle size of 3-in. and more than 20 percent plus 3/4-in. material may be dominated by those of the plus 3\4-in. material.

b. Plastic fines. The trends of Figures 127 and 130 taken together very quickly dispel the occurrence of optimum gravel content as explaining the higher maximum dry unit weights obtained for Gradations 3 and 4 between the Minus 2 in. gradations and Minus 3-in. gradations. From Figure 129 it is seen that the maximum dry unit weight for the Minus 2-in. gradations 3 and 4 (mold size is not a variable) does not reach an optimum value with increasing gravel content. Therefore, the peak in the bandwidth of Figure 127 caused by higher maximum dry unit weights obtained on Minus 2-in. Gradations 3a and 4a is attributable to mold size effects. So, at gravel content above about 50 percent, mold size effects began to occur for the clayey gravels between tests performed in the 12-in. and 18-in. molds. With this argument in hand, it can be said looking over all of the data in Figures 128 and 129 that the minor data point misalignments between Minus 2-in. and Minus 3-in. gradations are probably attributable to mold size effects in general and more exaggerated the more plastic the fines.

75. Figures 130 through 134 present the data in a form suitable for showing the effects of degree of scalping on maximum dry unit weight. Figures 130 and 131 treat the minus 3-in. full-scale gradations as the "parent" gradations and compare their maximum dry unit weights to those of the respective minus 2-in., minus 3/4-in. and minus No. 4 sieve fractions on the basis of the percentage by weight of the "parent" gradations scalped to produce the fractions. In a similar manner, Figures 132 and 133 treat the minus 2-in. gradations as the "parent" gradations and Figure 134 treats the minus 3/4-in. materials as the parent gradations. Of primary interest is the question; "How much material may be scalped and still obtain a reasonably accurate value of maximum dry unit weight for the parent material directly from the fraction?" To attempt a general and conservative answer to the question, a maximum permissible error of 2.5 lbs/cu ft less than the "parent" gradation value is adopted because it represents about two percent of the average maximum dry unit weights for the range of materials tested with maximum particle sizes greater than the minus No. 4 sieve size. In addition, except for minus 3-in. full-scale gradations 3 and 4 containing clay fines (Figure 131) where mold size effects were more pronounced, data on each figure are fitted through the point of zero deviation from the "parent" maximum dry unit weight at zero percent scalped. Using the maximum permissible deviation of fraction maximum dry unit weight from "parent" maximum dry unit weight of 2.5 lb/cu ft, the apparent maximum permissible degrees of scalping for each gradation are summarized in Table 41. The data of Table 41 are plotted in Figures 135 and 136 against gravel content in the "parent" gradation.

76. The data of Figures 135 and 136 are fitted with straight lines through zero percent scalping at zero gravel content. There is considerable scatter of the data about those straight lines but they are affixed to allow at least some degree of general assessment of the current 5 percent scalping rule of EM 1110-2-1906. A logical result is seen from the trend of the data in the two figures in that the higher the gravel content of the parent gradation, the larger the amount of material which can be scalped without severely affecting the value of maximum dry unit weight obtained on the scalped fraction. However, this trend runs counter to the current presumption that materials containing small amounts of gravel can tolerate the discarding of that

oversized fraction. Indeed, the straight line fits of Figures 135 and 136 indicate that soils containing less than 15 to 20 percent gravel should not be routinely subjected to as much as 5 percent scalping for determination of maximum dry unit weight.

77. The data of Table 41 are also plotted against percent minus No. 200 sieve size in the "parent" gradation in Figures 137 and 138. Table 41 paired with Table 19 describing the test gradations reveals that the permissible degree of scalping decreases consistently for both silt and clay fines with increasing fines in the parent gradation. Figures 137 and 138 imply an extreme sensitivity of permissible scalping with very small changes in percent fines in the parent gradation. The test gradations do not allow anything more than a raising of the question of the effects of percent fines. A thorough investigation would require comparisons of gradations with the same gravel fraction gradations but with different percentages of fines. With respect to the effect of plasticity of fines, all of the gradations exhibited very similar orders of sensitivity to scalping other than the minus 2-in. gradations containing clay fines which were distinctly less tolerant. None of the minus 2-in. gradations containing clay fines would tolerate as much as 10 percent scalping.

78. In turning back to the question of how much material can be scalped without significantly affecting the maximum dry unit weight, the data of Table 41 and the generalized linear fit to Figures 135 and 136 do not support the guidance of EM 1110-2-1906 with respect to use of generalized scalping practices. The manual currently permits scalping of plus No. 4 material as long as that total fraction constitutes less than 5 percent by weight of the total gradation. Compaction tests are then performed on the scalped fraction in the 4-in. diam mold and the maximum dry unit weight and optimum water content obtained are assumed to be equivalent to those of the total material. Similarly, scalping of up to 5 percent by weight of plus 3/4-in. material is permitted for compaction tests in the 6-in. diam mold and up to 10 percent by weight of plus 2-in. material is permitted for tests in the 12-in. diam mold. It is recalled that the 10 percent allowance for the 12-in. mold test is an inconsistency in the manual and should have also been revised to 5 percent. For the 12-in. mold test, the 5 percent scalping allowance is likely to be acceptable because materials tested in that sized mold will more likely contain more than 15 to 20 percent gravel. However, there is clearly no "pat"

answer to the question of how much scalping is too much. It can only be said that the answer is dependent on plasticity of fines, fines content and gravel content, i.e, plasticity and gradation. Where maximum dry unit weight determination is concerned, care should be taken in scalping even as little as 5 percent if the parent gradation contains less than 15 to 20 percent gravel.

79. The curves of Figures 139 and 140 present maximum dry unit weight versus maximum particle size in a manner intended to indicate the effects of plasticity of fines. Figure 141 presents the same data against gravel content. The shaded areas in the figures are bounded by curves which pair identical gradations, one with the silt fines and the other with the clay. The vertical bandwidths of these areas then indicate the difference in maximum dry unit weight due to varying the plasticity of the fines. The bandwidths indicate densities for gradations formed from minus 3/4-in. material containing 10 percent gravel (Gradations 1 and 2) were increased by 5 to 7 pcf when the minus No. 200 sieve material was changed from clay to silt while those for gradations formed from minus 3/4-in. material containing 40 percent gravel (Gradations 3 and 4) were increased by approximately 10 pcf. Figure 141 reveals the differences to be fairly constant over the range of materials tested but decreasing slightly and tending to converge with increasing gravel content.

Optimum water content

80. Figures 142 and 143 show the changes in optimum water content with successive scalping for test materials having nonplastic and plastic fines, respectively. The bandwidths again show how the changes occurred as additional plus 3/4-in. material was added to identical minus 3/4-in. fractions, i.e, from Gradation 1 to Gradation 2 and from Gradation 3 to Gradation 4. The curves of these figures show that optimum water contents increased with decreasing maximum particle size as would be anticipated because maximum dry unit weights increased in the same direction. Figures 144 and 145 show the data as a function of gravel content where it is again seen as it was for maximum dry unit weight that Gradations 1 and 2 can be taken together as one trend and Gradations 3 and 4 as another.

a. Non-plastic fines. For the gradations containing nonplastic fines shown in Figure 142, the addition of plus 3/4-in. sizes decreased optimum water contents on the average by approximately one percent in the case of materials having minus 3/4-in. fractions containing 10 percent gravel (Gradationsl and 2) and approximately 0.5 percent in the case of materials having minus 3/4-in. fractions containing 40 percent gravel (Gradations 3 and 4). The curves of Figure 144 presenting the same data plotted against gravel content provide the obvious explanation for the difference in the two ranges. Simply put, the minus 3/4-in. fractions of Gradations 3 and 4 which contain 40 percent gravel have already seen the major impact of gravel content on optimum water content (about 60 percent of the difference between minus No.4 and minus 3-in. gradations) and are relatively insensitive to the addition of more gravel. In contrast, the minus 3/4-in. fractions of Gradations 1 and2 with only 10 percent gravel have experienced only about 30 percent of the difference between minus No.4 optimum and minus 3-in. optimum. It can also be seen from Figure 144 that the values of optimum water content for all four gradations are tending to converge above a gravel content of about 50 percent.

b. Plastic fines. Figures 143 and 145 show the changes in optimum water content for the gradations with plastic fines plotted against maximum particle size and gravel content, respectively. As was observed for non-plastic fines, Figure 143 shows that the addition of plus 3/4-in. sizes again had more impact between Gradations 1 and 2 than between Gradations 3 and 4. Figure 145 showing the data in terms of gravel content provides the same explanation as was apparent for the silt fines in that the minus 3/4-in. fractions of Gradations 3 and 4 (40 percent gravel) already reflect about 70 percent of the total change in optimum water content over the range of fractions tested while the minus 3/4-in. fractions of Gradations 1 and 2 (10 percent gravel) have experienced 40 percent of the total change from the minus No.4 fractions to the minus 3-in. materials. The values of optimum water content for all gradations again appear to be converging near a gravel content of 50 percent.

81. As was done for maximum dry unit weight in Figures 130 through 134, Figures 146 through 150 treat each maximum particle size group of gradations as "parent" gradations and compare their optimum water contents to those of their fractions. Based on the average value of optimum water content of about 7 percent for all the gradations with both non-plastic and plastic fines which contained gravel, a maximum permissible deviation in optimum water content of 10 percent of the average or 0.7 percentage points below the "parent" gradation value was used to estimate maximum permissible degrees of scalping to obtain "parent" gradation optimum water content from that of a fraction. The data trends of Figures 146 through 150 did not consistently appear to pass through zero deviation from the "parent" gradation values. This may be the result of testing precision and the fact that optimum water contents are estimated by fitting a more or less parabolic curve through the compaction test data suite. These inconsistencies in the plots of Figures 146 through 150 are much more pronounced than those for maximum dry unit weight values of

Figures 130 through 134. It can be seen that "adjustments" to make the data trend through zero deviation would require generally less than one percentage point change in data points corresponding to the lowest degrees of scalping. In order to at least imply the useful limits of the current 5 percent scalping rule, the authors forced the curves through zero deviation by placing less credence in the low degree of scalping data points as seen in Figures 146 through 150. Therefore, the maximum permissible scalping values summarized in Table 42 are entirely the authors' judgment calls based on those forced fits. Figures 151 and 152 show the values of Table 42 fitted with a straight line through zero scalping at zero gravel content as was also done in Figures 135 and 136 for maximum dry unit weight. That presumed straight line fit indicates that the current 5 percent scalping rule would not be satisfactory for gradations containing less than about 15 to 20 percent gravel to achieve a precision of about 10 percent of mean value of optimum water content. This finding is identical to that for maximum dry unit weight and also clearly contradicts current practice. In other words, as gravel content decreases, the gradation's sensitivity to scalping with respect to optimum water content increases such that gradations containing 5 percent or less gravel are the very most sensitive to the removal of any material. Probably because of the inconsistencies just mentioned, there were no patterns discerned from Table 42 for all gradations with respect to plasticity of fines, percent fines or percent gravel. The minus 2-in. gradation data for both silt and clay fines exhibited generally increasing permissible scalping with increasing gravel content. The minus 3-in. data did not. The Nos.1 and 3 gradations with silt fines (Figure 146) and the No.3 gradation with clay fines (Figure 141) with a maximum particle size of 3-in. and the minus 3/4-in. gradation with clay fines (Figure 150) could apparently tolerate very little to no scalping at all. When Table 41 for maximum dry unit weight is compared to Table 42 for optimum water content, it becomes even more clear that no procedure based on fixed values of minimum scalping can provide satisfactory numbers for both parameters for all gravelly materials.

82. Figures 153 and 154 compare optimum water contents on the basis of plasticity of fines and maximum particle sizes. The bandwidths shown in these two Figures are obtained between like gradations with different plasticity of fines. Figure 155 plots the same data as a function of gravel content and again shows bandwidths on the basis of Gradations 1 and 2 paired against

Gradations 3 and 4 on the basis of plasticity of fines. The effects of plasticity of fines was essentially a constant for each of the four gradations over the range of particle sizes tested. Figure 153 indicates that optimum water content shifted about 3 percentage points wetter for Gradations 1 and 2 from non-plastic to plastic fines. The bandwidth for Gradation 2 showed the greater total change in optimum water content because the minus 2-in. and minus 3-in. fractions contained more gravel than in corresponding fractions of Gradation 1. Figure 154 reveals a similar picture for Gradations 3 and 4 but the bandwidths are about half those of Gradations 1 and 2, i.e., a change in optimum of about 1.5 percentage points wetter with a change from non-plastic to plastic fines. It is seen in Figure 154 that the data bands are separated according to the gradation of the minus 3/4-in. fractions although, as has been pointed out before, the bands tend to merge above about 50 percent gravel content.

Maximum dry unit weights versus optimum water contents

83. Figures 156 through 159 compare the "lines of optimum" for each gradation between non-plastic and plastic fines. It is interesting to note that at the lower gravel contents of Gradations 1 and 2 (Figures 156 and 157) the lines of optimum appear to be separate but at the higher gravel contents of Gradations 3 and 4 (Figures 158 and 159) they tend to merge. The "hooks" in the curves for Gradations 3 and 4 between minus 2-in. and minus 3-in. materials are attributed to mold size effects which are more severe for the plastic fines as previously discussed.

Correcting Maximum Dry Unit Weight and Optimum Water Content to Account for the Effects of Gravel

Corps of Engineers, EM 1110-2-1911

84. With respect to correcting fill density test results for the total material to obtain the corresponding dry unit weight and water content of some fraction, the USACE has often employed the equations given in EM 1110-2-1911, Appendix B, which are as follows:

For correcting dry unit weight of the total material:

$$\gamma_f = \frac{f\gamma_t\gamma_w G_m}{\gamma_w G_m - c\gamma_t} \qquad (1)$$

where

γ_f = dry unit weight of the fraction, pcf

γ_t = dry unit weight of the total material, pcf

γ_w = unit weight of water, 62.4 pcf

G_m = bulk specific gravity of oversize particles, dimensionless (see EM 1110-2-1906,"Laboratory Soils Testing", Appendix IV)

f = proportion of finer fraction by weight of total material expressed decimal fraction

c = proportion of coarser or oversize particles by weight of total material expressed as decimal fraction (note f + c = 1.00)

For correcting water content of the total material to obtain that of a fraction:

$$w_f = \frac{w_t - Cw_c}{f} \qquad (2)$$

where

w_f = water content of finer fraction, percent

w_t = water content of total material, percent

w_c = water content of coarser (oversized) fraction, percent, which is taken as the absorption, A, of the gravel in EM 1110-2-1911

f,c = as defined for Equation (1) above

85. Equation (1) was originally derived by Ziegler (1948). The manual states that the usefulness of the density correction Equation (1) is limited to cases where the proportion of oversize material is not greater than about 35 percent by weight. The reason for that limitation actually applies to a modified version of Equation (1) and will be clarified later in this section. Also note that Equation (2) differs from the version stated in EM 1110-2-1911 in that the manual shows the absorption of the gravel as the water content of the oversized material. Equation (2) is the correct general form of the relationship and must be true if the actual water contents of the two fractions are entered. A brief discussion of the effects of using the absorption as the water content of the oversize fraction will also be provided later in this section. The forms of equations (1) and (2) are intended for use in correct-

ing the fill dry unit weight and water content of the total material (obtained from the fill density test) to obtain those values for a fraction which are then compared to the maximum dry unit weight and optimum water content of that fraction to assess compliance with specifications which are referenced to the compacted state of that fraction. The maximum dry unit weight and optimum water content of the fraction are obtained in a convenient smaller mold such as the 4-in. mold for the minus No.4 sieve fraction or the 6-in. mold for the minus 3/4-in. sieve fraction or may be estimated using the one-or two-point compaction methods previously described. The compaction specifications for the fraction should have been derived on the basis of assuring satisfactory properties of the full-scale material. However, when compaction specifications have been based on a fraction, it has been typical that no large scale tests of total materials have been conducted to verify that the specifications on the fraction assure equal or better qualities of the total material.

86. It has also been the practice to use rearranged versions of Equations (1) and (2) to predict the maximum dry unit weight and optimum water content of the total material by substituting values of maximum dry unit weight and optimum water content for a fraction, respectively, and then compare the fill dry unit weight and water content for the total material directly to the predicted full-scale values. The maximum dry unit weight and optimum water content of the fraction are either obtained in the 4 or 6-in. mold or estimated by the one- or two-point compaction test method. In this case, the specifications must be written concerning the compacted state of the total material. Again, specifications written around the total material may have been adopted on the basis of testing of either the minus 3/4-in. or minus No. 4 fractions during the design phase and on the assumption that satisfactory states of compaction of those fractions could be directly translated to the total material. The attempt to use the concepts of Equations (1) and (2) to predict maximum dry unit weight and optimum water content of the total material first requires that their terms be rearranged to obtain dry unit weight and water content of a total material from the values for a fraction. The rearranged version of Equation (1) for estimating dry unit weight of the total material from that of a fraction is as follows:

$$\gamma_t = \frac{\gamma_f \gamma_w G_m}{F\gamma_w G_m + C\gamma_f} \qquad (1a)$$

The rearranged version of Equation (2) used for calculating the water content of the total material from that of a fraction becomes:

$$W_t = fW_f + CW_c \qquad (2a)$$

When Equation (1a) is used to predict the maximum dry unit weight of the total material by entering the maximum dry unit weight of a fraction, Equation (1a) is converted to:

$$\gamma_{tmax} = \frac{\gamma_{fmax} \gamma_w G_m}{F\gamma_w G_m + C\gamma_{fmax}} \qquad (3)$$

When Equation (2a) is used to predict the optimum water content of the total material by entering the optimum water content of a fraction, Equation (2a) is converted to:

$$W_{topt} = fW_{fopt} + cW_c \qquad (4)$$

87. Equation (1) is a straightforward weight-volume relationship easily derived by association of all variable volume of voids with the fine fraction. The variable volume of voids is the volume of voids which changes with densification of the material. Therefore, the equation simply divides the material into two fractions, accounting for the contribution to dry unit weight of each. Fundamentally then, its accuracy is contingent upon the condition that the finer fraction must completely fill the voids between the larger particles. In other words, there must be no extraordinary voids representing discontinuities in the mixture. This condition upon the accuracy of Equation (1) has proven to be generally unrestrictive in practice because maximum gravel contents usually encountered (say, less than 60 percent) do not result in par-

tially filled voids among the gravel particles. This same condition must be met for Equation (3) but there is a second condition required as well because of the modification to obtain the maximum dry unit weight of the total material.

88. The second condition on accuracy of Equation (3) represents the weakness of the use of that equation to predict the maximum dry unit weight of the total material from the maximum dry unit weight of a fraction. The entry of the maximum dry unit weight of the fraction into Equation (3) is tantamount to assuming that the increase in maximum dry unit weight of the total material with increasing gravel content results only from the addition of gravel weight of solids while the fraction remains at its maximum dry unit weight. In reality, as will be shown later in this report, the dry unit weight of the finer fraction in the total material when that total material is at its maximum dry unit weight is affected by the added gravel. The effect is such that the dry unit weight of the fraction may be greater than or less than its maximum value depending on the material and its gravel content. Thus, use of Equation (3) may result in either under-prediction (at lower gravel content) or over-prediction (at higher gravel content) of maximum dry unit weight of the total material. This is the reason that an "approximately equal" symbol is shown in Equation (3). For the case of use of the minus No.4 fraction as the finer fraction in Equation (3), the gravel content above which use of its maximum dry unit weight will begin to seriously over-predict the maximum dry unit weight of the total material has been empirically estimated to be about 35 percent. Hence, the aforementioned restriction on use of the equation is stated in EM 1110-2-1911. Unfortunately, under-prediction of the maximum dry unit weight was never addressed but may be significant as will be shown later. Furthermore, soils have been encountered for which use of the maximum dry unit weight of the minus No. 4 fraction with Equation (3) significantly over-predicts the maximum dry unit weight of the total material at gravel contents less than 35 percent. There is nothing to preclude use of the dry unit weight of the minus 3/4-in. fraction with Equation (3). This alternative will also be addressed in this report.

89. It is important to emphasize that Equation (3) is only an approximate expression where the equal sign must be replaced with an "approximately equal" symbol and very careful restrictions placed on the range in gravel content over which that approximation is acceptably accurate. So, Equa-

tion (3) is no longer Ziegler's equation and is not a true weight-volume relationship except at some singular value of gravel content where the fraction happens to exist at its maximum dry unit weight when the total material is also at its maximum dry unit weight.

90. Just as there is no reason to expect the maximum dry unit weight of a fraction entered into Equation (3) to generally yield the maximum dry unit weight of the total material, there is no reason to expect the optimum water content of a fraction entered into Equation (4) to generally yield the optimum water content of the total material. When the compaction curves for a total material and a fraction thereof are compared, the optimum water content of the total material will always be dryer than that of the fraction. If the optimum water content of the fraction entered into equation (4) is to generally yield the optimum water content of the total material, then the water content of the oversized gravel must always be precisely such as to account for the difference in optimum water contents between the fraction and the total material. This is not true as will be shown later and the water content of the fraction must be altered to produce optimum water content (i.e., 100 percent compaction) of the total material. That is to say, the fraction is generally not at its optimum water content when the total material is except for a singular value of gravel content in the total material. Therefore, Equation (4) must also be written with the approximately equal symbol and restrictions placed on range in gravel content over which the approximation is acceptably accurate.

91. The full-scale and associated minus 3/4-in. sieve scalped/replaced data obtained by Donaghe and Townsend (1975) can be used to gain a preliminary insight into potential errors introduced by using the maximum dry unit weight of the minus No. 4 fraction with Equation (3) in attempting to predict a value of maximum dry unit weight for the total material. Figure 30 showed the results of such predictions for the full-scale materials. The values of total material maximum dry unit weight predicted from those of the minus No. 4 fractions reasonably track the actual values up to a gravel content in the total material of about 35 percent. However, it is to be noted that the total materials were compacted in the 18-in. diam mold by mechanical compactor while the minus No. 4 fractions were compacted in the 4-in. diam mold with a hand-held rammer. These two test procedures would not yield identical compaction parameters for the same minus No. 4 material. Therefore, mold size and procedural

effects played a significant role in the adequacy of predicted values up to 35 percent gravel content.

92. Figure 31 is companion to Figure 30 and shows the same comparative data relative to minus 3/4-in. sieve scalped/replaced gradations derived from the full-scale materials shown in Figure 30. Between Figures 30 and 31 the minus No. 4 fractions are the same and the respective percentages of gravel are the same. So, a scalped/replaced gradation can be viewed as just another material with all characteristics identical other than a more uniformly graded gravel fraction. Also, all the scalped/replaced data of Figure 31 were obtained in the 6-in. mold with a hand-held rammer so that at zero gravel content there is no appreciable difference in the maximum dry densities between the 6-in. mold and the 4-in. mold. It has been fairly well established that compaction tests performed on a minus No. 4 material in both the 4 and 6-in. diam molds can be taken as equivalent. Figure 31 shows that the predicted values of the maximum dry unit weight of the scalped/replaced gradations were consistently and significantly higher than the actual values.

93. Since the minus No.4 fractions between Figures 30 and 31 are the same and also the respective gravel contents, it is evident that Equation (3) may adequately predict the maximum dry densities for one family of gradations up to about 35 percent gravel (full-scale materials, Figure 30) but not perform satisfactorily at all for another family of gradations (scalped/replaced, Figure 31). It was pointed out in the previous section that scalped/replaced gradations will not generally replicate the maximum dry densities of parent full-scale materials. Therefore, the common minus No.4 fraction data of Figures 30 and 31 used with Equation (3) do not adequately predict both gradations' maximum dry densities for any gravel content.

94. The authors wish to provide more clarification of the extent to which Equations (3) and (4) are useful to predict the maximum dry unit weight and optimum water content of a total gradation from those values obtained for the fraction. That is, if the maximum dry unit weight of a fraction is entered into Equation (3), will the calculated dry unit weight for the total material correspond to its maximum dry unit weight? Likewise, if the fraction's optimum water content is entered in Equation (4), will the calculated water content for the total material match the value of its optimum water content?

95. The usefulness of the equations for prediction purposes will be assessed first by attempting to account for equipment size effects (corrected data) and then by ignoring those effects (uncorrected data). Conventional past usage of the equations would correspond to the uncorrected case. Correction for equipment size effects was addressed by testing each minus No. 4 and minus 3/4-in. fraction in the same equipment using the same procedures used to test corresponding larger particle size parent materials. Therefore, in applying Equations (3) and (4) to predict minus 3-in. and minus 2-in. compaction parameters, the values of maximum dry unit weight and optimum water content taken into the equations for the fractions were those numbers obtained for the fractions in the corresponding sized molds (see Tables 27 and 29). Although it may be reasoned that equipment size effects may be accounted for in this manner, it is an imperfect approach in the absence of precision considerations. Further, the water content of the oversize is taken as its air-dry value (0.6 percent) because the gravel was added to the wetted and cured fractions in this condition immediately prior to compaction. There were no specific measurements to determine any changes of fractions' water contents after mixing and compaction. The authors are of the opinion that there would have been insignificant change in the water contents of the components because of the short time between mixing and compaction. There will be several figures presented below in which differences between calculated values and actual values will be plotted versus other parameters. It is important to realize that "actual" values are random numbers within the precision of the test. And, precision varies with plasticity of fines as seen from the previously presented ACIL and USACE multilaboratory studies. Therefore, there is an inherent and invisible "slop" in results. It is appropriate to avoid undue confidence in any discrete data comparisons and concentrate upon apparent trends. Consequently, the authors will avoid point by point comparisons of the data. After examining use of Equations (3) and (4) taking equipment size effects into account, the exercise will be repeated with those effects unaccounted for by entering the equations with maximum dry unit weights and optimum water contents of the minus No. 4 and minus 3/4-in. fractions obtained in the 6-in. diam mold. The most practical value of the equations is in their use with data obtained in the smaller mold.

Predicted maximum dry unit weight with fraction data corrected for equipment size effects

96. Plots of calculated dry unit weights minus actual values of maximum dry unit weight versus percent oversize material for minus 3-in. and minus 2-in. gradations with both plastic and non-plastic fines are given in Figures 160 and 161, respectively. The straight lines shown connecting data points in Figures 160 and 161 are not indicative of trends, but are used to aid the reader in associating the points with corresponding gradations. In order to obtain a more complete picture it is advantageous to also plot the deviations against the gravel contents of the total materials as in Figures 162 and 163 (again, the straight lines connecting points have no trend significance). Judgment of the extent of usefulness of Equation (3) with the maximum dry unit weight of a fraction to predict the total material maximum dry unit weight requires the adoption of conservative precision limits. For this purpose, two percent single-operator precision limits are believed to be unconservative, i.e., too broad. This opinion is supported by the precision achieved among different mold sizes as previously discussed and shown in Tables 25 and 27 and the fact that those data still reflect equipment effects. In addition, the RRL comparative compaction program previously discussed (see paragraph 39) showed a single-operator precision for tests in a 4-in. mold on a CH material to be about 2.2 percent. Clean CH soils are the most problematical to establish compaction curves for. Single-operator precision for CL and ML soils should be somewhat better. The addition of gravel reduces the overall plasticity of the total material for clayey fines. The authors submit that a one percent precision limit is more appropriate than a two percent limit for assessing the prediction of maximum dry unit weight of total materials using Equation (3). An approximation of these precision limits is shown as the dashed lines in Figures 160 through 163 and in all subsequent similar plots. For the sake of simplicity, the approximate equivalent to one percent precision limits was taken as one percent of an average value of maximum dry unit weight of all the materials at 130 lb per cu ft. Rigorous application of precision would be by averaging the predicted and actual (test) values and taking one percent of that number. Use of the approximate limits does not negate the objectives since for the maximum difference seen for any pair of unit weights (actual versus predicted), the correctly calculated precision range would deviate from the approximate range by less than 0.05 lb per cu ft.

97. Figures 160 through 163 treat both the plus No. 4 sieve fraction and the plus 3/4-in. fraction as "over-size". Table 43 provides a summary of the discrete data. Scrutiny of the data of Figures 160 through 163 reveals that even though there appear to be some effects of plasticity of fines and maximum particle size (minus 3-in. gradations versus minus 2-in.), the differences are small in light of testing precision. Figures 164 and 165 combine the minus 3-in. (Figure 161) and minus 2-in. (Figure 163) data for predictions based on the minus No.4 and minus 3/4-in. fractions, respectively. Note that a new set of predictions of maximum dry unit weight are shown in Figure 164 which are those for the minus 3/4-in. fractions predicted from the minus No. 4 fraction where both fractions were compacted in the 6-in. diam mold. The discrete data for these predictions are given in Table 44. Estimated band widths based on plasticity of fines are also drawn in Figures 164 and 165 and confirm the relatively small effects that parameter seems to represent. The authors warn that combination of the prediction data for Gradations 1 and 2 and for Gradations 3 and 4 as well as for minus 3-in., minus 2-in. and minus 3/4-in. gradations carries the risk that all these are really separate trends. There are some implications of this in Figures 162 and 163, especially with respect to Gradations 1 and 2 as opposed to Gradations 3 and 4. The width of the bands shown in Figures 164 and 165 may or may not properly encompass these differences.

98. Care must also be exercised in judging the implications of Figures 160 and 161 where deviations are plotted against percent oversize. These figures actually present a "mixed bag" in that one fraction contains gravel and the other does not. Percent oversize for the minus No. 4 fraction is, of course, percent gravel. While Figures 160 and 161 indicate that use of the minus No. 4 fraction with Equation (3) allows acceptable predictions of maximum dry unit weight at higher percent oversize than does use of the minus 3/4-in. fraction, percent oversize is not the most pertinent issue. It is more significant to see from Figures 161 through 165 that the use of the minus 3/4-in. fraction in the predictions will permit the treatment of total gradations containing higher percent gravels. This was a logical expectation but it had to be shown that nothing anomalous occurred with the use of a fraction containing gravel itself for prediction purposes. Figures 160 and 161 do reflect the effects of gradation on prediction accuracy. As the gradation of the oversize (or gravel) fraction becomes less well graded as it does from

Gradation 1 to Gradation 4, the deviation of predicted value from actual value tends to increase. This effect is particularly evident for the predictions made with the minus 3/4-in. fraction data because the percent oversize is identical for Gradations 1 and 3 and for Gradations 2 and 4 and yet the deviations of predicted values from actual values for Gradations 3 and 4 with the more uniform oversize gradations are greater than those associated with Gradations 1 and 2 with more well graded oversize fractions. Similar implications can be seen in Figures 164 and 165 although much less distinct.

99. It is interesting to note from Figures 164 and 165 that at lower gravel contents, Equation (3), whether entered with the maximum dry unit weight of the minus No. 4 or minus 3/4-in. fraction, tends to under-predict the actual maximum dry unit weight of the parent gradation. Since the one percent precision limits are conservative, the degree of under-prediction at lower gravel contents indicated in Figures 164 and 165 are not deemed to be serious. It was previously pointed out in the discussions of maximum permissible degrees of scalping (paragraph 51) that the addition of very small quantities of gravel to the minus No. 4 materials resulted in strong increases in maximum dry unit weight. The fact that Equation (3) under-predicts in this range suggests that the dry unit weight increase cannot be explained only by the addition of the solid particles. As will be more thoroughly addressed later in this report, the authors speculate that the minus No.4 material between two particles or between a particle and the mold boundaries undergoes additional densification compared to that minus No. 4 material outside that zone of particle influence as the rigid particles are forced closer together or closer to the mold boundaries during compaction. The net effect is an average dry unit weight in the minus No. 4 fraction which is greater than its standard effort maximum dry unit weight. A similar effect seems to also exist when gravel is added to a minus 3/4-in. fraction. The concept of "gravel interference" will be presented in Part VII.

Predicted optimum water content with fraction data corrected for equipment size effects

100. Calculated water contents minus actual values of optimum water content are identified by specific test gradations versus percent by weight of oversize material for 3 and 2-in. maximum particle sizes in Figures 166 and 167, respectively. The straight lines connecting data points are only to

aid the reader in associating corresponding gradations. Calculated values were obtained using Equation (4) with optimum water contents determined for the respective fractions tested in the same molds as the 2 and 3-in. maximum particle size parent materials along with the air-dry water content of the gravel of 0.6 percent. The discrete data are summarized in Table 45. Figures 168 and 169 present the deviations plotted against gravel content in the parent gradations. As was the case for predicting maximum dry unit weight, the authors chose to reject the currently suggested precision limit of 10 percent for optimum water content. The RRL study (see paragraph 32) indicated a single-operator precision of about 5 percent. The approximate test precision range of 5 percent of an average optimum water content of 7 percent is adopted and indicated by the dashed lines at ± 0.35 percentage points in these figures. There appear to be somewhat greater effects of plasticity of fines on predictions of optimum water content than were apparent for maximum dry unit weight. These effects are more clearly seen in Figures 170 and 171 where the data of Figures 168 and 169 are combined along with the added predictions of optimum water content of the minus 3/4-in. materials from that of the minus No.4 fractions. The ranges of the deviations of predicted value from actual value are shown as bands according to plasticity of fines. The discrete data for predictions of minus 3/4-in. gradations' optimum water content from that of the minus No.4 fractions are given in Table 44. The previous warning that combination of results seen for Gradations 1 and 2 with those for Gradations 3 and 4 as is done in Figures 170 and 171 may be risky is also appropriate for the optimum water content predictions. The gradation of the oversize or gravel fraction has a similar but more muted effect on predictions of optimum water content than upon those of maximum dry unit weight. As in the case of maximum dry unit weight, it is seen by comparison of Figures 170 and 171 that use of the minus 3/4-in. fraction permits acceptable prediction of optimum water content at higher gravel content in the parent gradation than does the minus No.4 fraction. Figure 170 for the minus No.4 fraction also shows that the predicted optimum water content of the total material may be relatively poor for gradations with plastic fines at lower gravel contents. This is aggravated by the fact the total material optimum values are of such a low order to begin with and typical specified placement ranges are no larger than plus or minus two percentage points with respect to optimum.

Predicted maximum dry unit weight with fraction data not corrected for equipment size effects

101. Figures 172 through 177 are companion to Figures 160 through 165 and are based on predictions of maximum dry unit weight calculated from Equation (3) by entering values of maximum dry unit weight for the minus No. 4 and Minus 3/4-in. fractions obtained in the 6-in. diam mold. The straight lines connecting data points in Figures 172 through 175 are only for the purpose of associating corresponding gradations and do not indicate trends. Use of the 6-in. diam mold parameters for the minus No.4 and minus 3/4-in. fractions introduces equipment size effects into the predicted values. The discrete data are summarized in Table 46. Note that in Figure 176 the data for the minus 3/4-in. fractions (see Table 44) is the same as that plotted previously in Figure 164 for "corrected" data since minus No.4 and minus 3/4-in. materials were both compacted in the 6-in. diam mold. Furthermore, it was previously pointed out that the results obtained on minus No. 4 material in the 4- and 6-in. diam molds showed no significant equipment size effects. Therefore, there is no difference in corrected and uncorrected data for these two fractions. The plots of Figures 172 through 175 are provided to allow the reader to associate the predictions with the particular gradations. Figures 176 and 177 are summary plots for the purpose of indicating the authors' interpretation of general trends. It is seen that the predictions are generally less satisfactory compared to those achieved with data corrected for equipment size effects. Figure 176 shows particularly depressing results with use of the minus No.4 fraction because the trends in predicted values (indicated by the estimated band widths) cut across the adopted precision range at a relatively steep slope from severe under-prediction of the actual maximum dry unit weight of the total material to sever over-prediction. This results in an intermediate range of gravel contents for which the predictions are satisfactory. There is little consolation in the fact that the maximum gravel contents for which predicted values may be satisfactory is somewhat higher than previously seen for corrected data. If Equation (3) yields relatively reliable predictions from very low gravel content up to some apparently consistent maximum gravel content, one can proceed with confidence if one knows the limit. However, the trends indicated in Figure 176 raise problems concerning the utility of the method. For uncorrected predictions based on minus 3/4-in. fractions as shown in Figure 177, the problem is less severe but would

still potentially negate the practical use of Equation (3) even considering the conservatism of the adopted precision limits. So, equipment size effects are a serious consideration when employing Equation (3) to predict the maximum dry unit weight of the total material from that of a fraction. Unfortunately, the only way to get around those effects would be to perform compaction tests on the fraction in the larger molds appropriate to the total material. This is generally not practical in the fill control operation. However, it may be feasible to perform enough testing during the project design phase to develop corrections for the magnitude of the mold size effects for the range of materials to be placed. It is particularly important that Equation (3) may tend to significantly under-predict the total material value at lower gravel contents if the data are not corrected for these effects by use of the proper mold size because this would lead to a general, erroneous inflation of percent compaction of the fill in the field compaction control procedures for such gradations. It is unfortunate that, as previously pointed out, it doesn't appear likely that a generalized correction approach can be developed which will satisfactorily address a range in plasticity of the fines. It is true that nonplastic silt fines represent differences which may be largely acceptable but this sort of gravel mixture has not been frequently encountered. Actual comparative testing in the different sized molds is indicated to establish the need for correction of small mold data and its magnitude.

Predicted optimum water
content with fraction data not
corrected for equipment size effects

102. Figures 178 through 183 are companion to Figures 166 through 171 and are based on predictions of optimum water content calculated from Equation (4) by entering values of optimum water content for the minus No. 4 and minus 3/4-in. fractions obtained from the 6-in. diam mold. The straight lines connecting data points in Figures 178 through 181 are only for the purpose of aiding the reader in associating gradations. The discrete data are presented in Table 47. Figures 178 through 181 associate the data with the specific test gradations while Figures 182 and 183 are summary plots to show estimated general trends. Comparisons among the corresponding figures reveals that correction of the data produced a general improvement in prediction of optimum water content just as it did maximum dry unit weight even though in

some cases such as that of the minus 3-in. gradations the uncorrected data provides slightly superior estimates.

Other prediction methods

103. AASHTO AND USBR. Both the American Association of State Highway and Transportation Officials (AASHTO) and the US Bureau of Reclamation employ an identical modified version of Equation (3) to compute maximum dry unit weight of the total material from that of the minus No. 4 fraction. Both agencies use Equation (4) for calculating water content. The AASHTO approach to predicting maximum dry unit weight is contained within their test designation T224-86, "Standard Method for Correction for Coarse Particles in the Soil Compaction Test" and the USBR method (USBR 1989b) is addressed in their test designation USBR 5515-89, "Procedure for Performing Laboratory Compaction of Soils Containing Gravel". The modified form of Equation (3) is as follows:

$$\gamma_{tmax} = \frac{I\gamma_{fmax}\gamma_w G_m}{f\gamma_w G_m + IC\gamma_{fmax}} \qquad (5)$$

where

γ_{tmax} = calculated maximum dry unit weight of the total material

γ_{fmax} = maximum dry unit weight of the minus No. 4 sieve fraction obtained in the 4-in. diam mold

γ_w = unit weight of water

γ_c = bulk specific gravity of the gravel

c = decimal percentage by weight of coarse or oversize fraction which is in this case the plus No. 4 fraction, i.e., the decimal percentage by weight of gravel

f = decimal percentage by weight of minus No. 4 fraction

r = fraction density factor defined as the calculated dry unit weight of the minus No. 4 fraction in the total material divided by its maximum dry unit weight, i.e., γ_f/γ_{fmax} or the percent compaction (expressed as a decimal) of the minus No.4 fraction in the total material

The modification of Equation (3) then amounts to substitution of the identity r γ_{fmax} for γ_f . The difference in the two organizations' practices lies in the difference in values of the fraction density factor assigned to the given total material based on its gravel content. The authors have been unable to find a reference which describes how the AASHTO developed its values. The

USBR bases its values on considerable testing experience and recommends their use only in the absence of more "precise" data.

104. NAVFAC. Naval Facilities Engineering Command (NAVFAC) presents a different approach to correcting the value of dry unit weight of either the minus No. 4 fraction or the minus 3/4-in. fraction to obtain that of the total material. NAVFAC also uses Equation (4) for calculating water content. The equation presented in their Design Manual 7.2, "Foundations and Earth Structures," 1982, is a follows:

$$\gamma_{tmax} = \frac{1 - (0.05)F}{\dfrac{F}{162} + \dfrac{(1 - F)}{\gamma_{fmax}}} \tag{6}$$

where

γ_{tmax} = calculated maximum dry unit weight of the total material, pcf

γ_{fmax} = laboratory maximum dry unit weight of either the minus No. 4 or minus 3/4-in. fraction, pcf, obtained in the 4- or 6-in. diam mold as appropriate

F = percent coarse or oversize fraction expressed as a decimal

The constant value of 162 in Equation (6) represents the term $G_m \gamma_w$ so that a constant value of bulk specific gravity of the oversized particles of 2.59 is assumed. Recognizing that the term (1-F) is the percent fine fraction expressed as a decimal, Equation (6) can be rearranged to the following form:

$$\gamma_{tmax} = \frac{(1 - 0.05c)\gamma_{fmax} G_m \gamma_w}{f G_m \gamma_w + c\gamma_{fmax}} \tag{7}$$

where all terms are the same as in Equation (6) except that as in Equations (1) and (3):

c = percent coarse fraction expressed as a decimal

f = percent fine fraction expressed as a decimal

Equation (7) can readily be seen to be Ziegler's Equation (1) multiplied by the factor (1 - 0.05c) and taking a constant value of bulk specific gravity of the gravel as 2.59. The NAVFAC DM 7.2 describes Equation (6) as a modified version of McLeod (1958). Examination of that ASTM reference reveals that

McLeod's method is precisely identical to Ziegler's. The authors have been unsuccessful at determining the Navy's rationale in applying the factor (1 - 0.05c).

105. Equation (7) can be equated to Equation (5) to derive an equivalent Fraction Density Factor, r , for the NAVFAC method. That derivation yields:

$$r = \frac{162f(1 - 0.05C)}{162f + 0.05C^2\gamma_{fmax}} \tag{8}$$

106. Before proceeding to compare Fraction Density Factors developed from this investigation with those offered by the USBR and AASHTO and those derived for NAVFAC, it is necessary to review some pertinent fundamental factors related to those comparisons. As best the authors can determine, the USBR and AASHTO factors are based on minus No. 4 fraction maximum dry unit weights obtained in the 4-in. diam mold employing a hand-held rammer. The NAVFAC equation is stated to be for use with either the minus No. 4 or minus 3/4-in. fractions. It was shown previously (see Figure 117) in this investigation that results obtained on minus No.4 fractions in 4 and 6-in. diam molds with the mechanical compactor may be taken as equivalent. It was also seen in review of the literature that shape and position of hand-held rammer compaction curves may differ from those obtained on the same material using a mechanical compactor. Unfortunately, this investigation did not include hand-held rammer compaction tests and previous investigations did not examine the subject other than in a very limited manner. An obvious supposition of this investigation in keeping with the objective of developing compaction procedures for earth-rock mixtures using a mechanical compactor is that all materials will be compacted with that equipment. If one chooses to believe that the same average value of maximum dry unit weight of the minus No. 4 fraction would be obtained from several replicate tests between the 4 and 6-in. diam mold by both hand-held rammer and mechanical compactor, the comparisons of Fraction Density Factors to follow can be accepted without caveat.

107. Figures 184 through 187 compare Fraction Density Factors developed from this investigation for minus 3-in. and minus 2-in. gradations with the USBR, AASHTO and derived NAVFAC values [Equation (8)]. Figures 184 and 185 show WES factors based on taking the fine fraction as the minus No. 4 material

while Figures 186 and 187 utilize the minus 3/4-in. fraction. Since both USBR and AASHTO designate the fine fraction to be the minus No. 4 material, their factors are based on data uncorrected for any equipment size effects. The WES data shown in Figures 184 through 187 include both that corrected and that uncorrected for equipment size effects. Corrected WES factors were calculated from Equation (5) by substituting values of the maximum dry unit weights of the minus 3-in. and minus 2-in. gradations and values of maximum dry unit weights for the designated fine fractions which were obtained in the same size mold as the total material values. Tables 48 and 49 show results of calculation of the corrected WES Fraction Density Factors. Uncorrected WES factors were calculated using maximum dry unit weights for the minus No. 4 and minus 3/4-in. fractions obtained in the 6-in. diameter mold. Tables 50 and 51 present the results of these calculations. Taking the minus No. 4 material as the fine fraction, Figures 184 and 185 show that Fraction Density Factors developed from this investigation were generally higher than those cited by the USBR and AASHTO with the WES uncorrected data yielding the highest values. It is also seen from Figures 184 and 185 that the WES corrected factors do not exceed 1.00 for the minus No. 4 fraction. The NAVFAC derived factors do not reflect nearly the sensitivity to increasing gravel content as compared to WES, USBR and AASHTO in Figures 184 and 185 but still fall within the range of the other three agencies' combined data. Taking the minus 3/4-in. material as the fine fraction, it is seen from Figures 186 and 187 that the WES factors generally cluster about the derived NAVFAC curve which is touted as also applicable to that fraction in addition to the minus No. 4 fraction. Unlike the minus No. 4 fraction, the WES corrected data for the minus 3/4-in. fraction shows it to exist in the mix above 100 percent compaction at a gravel content as high as 40 percent.

108. Table 52 gives the WES uncorrected Fraction Density Factors, the USBR, the average AASHTO and the derived NAVFAC factors for the minus 3-in. and minus 2-in materials tested in this investigation. Also shown are the calculated values of maximum dry unit weight of the total materials using the listed factors applied to the maximum dry unit weights of the minus No. 4 fractions. Of greatest significance among the data given in Table 52 are the differences in factors among the four agencies for the individual gradations and the differences in calculated maximum dry densities of the total materials which result. The maximum differences in Fraction Density Factor for each

gradation are plotted in Figure 188 where they are seen to vary from 0.03 to 0.04 at the lowest gravel content (Gradation 2A) up to as much as 0.08 or 0.09 for the highest gravel contents (Gradations 4 and 4A). The values of dry unit weight shown in Table 52 for WES are the actual maximum dry unit weights because the WES factors were derived using those numbers. So, the following is evident from the table:

a. Use of the USBR factors result in predicted values of maximum dry unit weight of the total material which range from 1.1 pcf higher than to 4.7 pcf lower than the actual value. The average deviation for the minus 3-in. gradations containing silt fines is 3.3 pcf lower than actual and is 1.1 pcf lower than actual for the minus 2-in. gradations with silt fines. The average deviation for minus 3-in. gradations with clay fines is 2.0 pcf lower than the actual value and for the minus 2-in. gradations with clay fines is 3.0 pcf lower than actual.

b. The AASHTO factors yield calculated values of the maximum dry unit weight of the total material which range from 2.2 to 6.1 pcf lower than the actual value. The average deviation for the minus 3-in. gradations with silt fines is 4.7 pcf lower than actual and is 3.6 pcf lower for the minus 2-in. gradations with silt fines. The average deviation for minus 3-in. gradations with clay fines is 4.2 pcf lower than actual and is 5.4 pcf lower for the minus 2-in. gradations.

c. The NAVFAC derived equivalent factors result in calculated values of maximum dry unit weight of the total material which range from 0.9 to 6.6 pcf lower than the actual values. For the minus 3-in. gradations containing silt fines the average deviation is 4.0 pcf lower than actual and is 3.2 pcf lower for the minus 2-in. gradations. The average deviation for the minus 3-in. gradations with clay fines is 3.2 pcf lower than actual and for the minus 2-in. gradations is 4.8 pcf lower.

Obviously, neither the USBR, the AASHTO nor the NAVFAC methods are satisfactory for the majority of the gradations tested by WES. To add a more general dimension to the assessment of "standardized" Fraction Density Factors, Figure 189 shows the factors calculated for all tests on gradations containing clay fines for this investigation and those discussed earlier in the review of the literature. The data of Figure 189 encompasses maximum particle sizes from 3/4-in. to 4-in., a wide range in shape of grain-size distribution curves, percent minus No. 200 sieve approaching 40 percent, and plasticity of the fines (minus No. 200 sieve sizes) ranging from clay (CL) to clay (CH). The authors believe that Figure 189 clearly indicates that the Fraction Density Factor (percent compaction of the fine fraction in the total material) is very much a function of the gradation and the plasticity. The bandwidth in factors evident in Figure 189 is about 0.10 throughout the range in gravel content. The point to be made from all these comparisons of Fraction Density Factors lies in Figure 190 which shows the serious impact of very small variations in the factor on the calculated value of dry unit weight of the total material. It appears that it is not a wise practice to utilize Fraction Density Factors unless they have been established specifically for the materials at hand over their range in gradations and plasticities. The use of generalized factors such as those offered by USBR, AASHTO and NAVFAC may lead to major errors and failure to actually control compaction.

PART VII: THE CONCEPT OF GRAVEL INTERFERENCE

General

109. The terms interference, particle interference and interference gravel content have been used previously in this report without definition. The authors purposely delayed discussion of the subject and an attempt to explain "interference" until after the reader had a chance to become familiar with the compaction characteristics of gravelly soils and the various factors which appear to affect those characteristics. Perhaps, the only safe statement to make regarding a definition of interference which might not arouse much contest is that it refers to the effects that added gravel has on the compaction of a finer fraction. By finer fraction, it is easiest to take that as a reference to the minus No. 4 fraction, i.e, that fraction containing no gravel. However, the finer fraction has also been taken as the minus 3/4-in. fraction within this report as well as by other investigators. In the discussion that follows, the minus No. 4 fraction will be synonymous with finer fraction. The reader should take note that the term "matrix" has been carefully avoided throughout this report. The authors can see only confusion from use of this term in treatment of characteristics or properties of earth-rock mixtures except in the special case of a very severely gap-graded material.

Hypothetical Interference Concepts

110. The differences of opinion concerning the definition of interference arise over whether or not the term is even appropriate or exactly what phenomena are believed to contribute to it. It was pointed out in discussion of the 1963 USBR report that particle interference was seen specifically as the development of voids between gravel particles which were not filled or partially filled with minus No. 4 material. This occurrence could only result in a depressed average dry unit weight of the minus No. 4 material. At the same time, the 1963 edition of the USBR Earth Manual contained the curves previously shown in Figures 184 and 185 which for clayey gravels indicates the percent compaction of the minus No. 4 fraction to exceed 100 percent at gravel contents below about 33 percent (data uncorrected for mold size effects). Figures 184 through 187 also show that this investigation found the minus

3/4-in. and No. 4 fractions of some gradations with both silt and clay fines to exist in the total material above their maximum dry unit weights at low gravel contents even if the data are corrected for equipment size effects. The USBR (see Figure 3) and Donaghe and Townsend (see Figure 30) showed increases in maximum dry unit weight with increase in gravel content which generally followed a smooth curve up to and even beyond the "optimum" gravel content (usually somewhere between 50 and 70 percent gravel). Garga and Madureira (see Figures 46 through 50) did not observe very smooth trends. The authors attribute this to, (1) an endemic problem with precision in compaction testing of large specimens which can also be seen in the data obtained during this investigation in Figures 118 through 125, and (2) the fact that Garga and Madureira calculated water contents of the total materials using an assumed value for water content of the gravel fraction. Because the four gradations at each maximum particle size tested in this investigation contained two different minus 3/4-in. fractions, only two total material maximum dry densities were obtained for each fraction for each maximum particle size. The two minus 3/4-in. fractions produced two different trends in maximum dry unit weight of the total material with only two gravel content points for each so that no assessment of the smoothness of trend in maximum dry unit weight can be made. Given a smooth transition of total material maximum dry unit weight, the calculated decline in dry unit weight of the minus No.4 fraction will also be a smooth curve with increasing gravel content in the parent gradation. Also, it is seen from Figure 189 that all referenced investigators found the dry unit weight of the minus No.4 fraction to be above 90 percent of standard effort maximum dry unit weight up to 50 percent gravel.

111. Figure 191 (Barnes, 1987) shows theoretical computations of spherical gravel particle separation for a cubical arrangement (loosest state) and a tetrahedral arrangement (densest state) for actual compacted materials for increasing gravel content and two water contents of the fine fraction (clay). It is seen from Figure 191 that the gravel content at which uniform spherical particles would come into contact (zero d/D ratio) decreases with decreasing water content of the fraction and lies somewhere between about 50 and 80 percent at the lowest water content of 12 percent. For gravelly soils containing non-uniform and non-spherical particles this range in "particle contact" gravel content appears to be somewhat lower and probably corresponds to the "optimum" gravel content with respect to maximum dry unit weight. At any

rate, at lower than "optimum" gravel contents the particles can still "float" in the finer fraction. Given the fact that the particles are floating in the finer fraction, the relatively high degree of compaction of the finer fraction and the smoothness of the trend in increasing maximum dry unit weight of the total material, it doesn't seem that the hypothetical interference factor of random unfilled voids is credible below the optimum gravel content.

112. Another hypothetical argument which has been advanced to explain at least a significant portion of the calculated decline in dry unit weight of the finer fraction with increasing gravel content is that excess voids develop about the gravel particles as the result of a rigid boundary effect. Hardin (1989) addresses this effect particularly with respect to the determination of the void ratio of sands using various sizes and shapes of molds. Soil specimens are commonly formed in rigid molds with a plane surface struck off at the top with a rigid straightedge. The rigid boundaries and plane surfaces interrupt the packing of the particles. When the volume of the specimen is computed from the volume of the mold and plane surfaces, additional void space at the boundaries that is not representative of the void ratio of a repeating element of the packing away from a boundary is included in that volume. Analogously, a rigid gravel particle imbedded in the finer fraction also represents an interruption of the particle packing of the fraction. Hardin experimentally verified the following theoretical expression for correcting the measured void ratio for the rigid boundary effects:

$$e_{corr} = e_{meas} - \frac{1.6 D_{10}}{6 \frac{V}{A}} \tag{9}$$

where

e_{corr} = void ratio corrected for rigid boundary effects

e_{meas} = measured void ratio

D_{10} = soil particle diameter at 10 percent finer by weight

V = volume of the mold

A = mold surface area (including any planar end surfaces)

Hardin included sands with subangular grain shape in his testing program and concluded that Equation (9) is nearly independent of grain shape. He examined this experimental conclusion in light of the theory leading to Equation (9) and confirmed that grain shape should not significantly alter the boundary effects.

113. Before discussing adaptation of Hardin's approach to consider boundary effects produced by a gravel particle imbedded within the minus No. 4 material, it is first instructive to use Equation (9) to determine the minimum value of D_{10} requiring correction to the void ratio of a material placed within the 4-in. and 18-in. diam compaction molds used in the investigation. In order to do this, it will be assumed that a significant correction to measured void ratio is 0.005. The calculations are as follows:

a. For the 4-in. diameter mold:

$V = 1/30 \text{ cu ft} = 943.89 \text{ cm}^3$

$A = 533.74 \text{ cm}^2$

$V/A = 1.768 \text{ cm}$

substituting into Equation (9)

$$0.005 = \frac{1.6D_{10}}{6\,\frac{V}{A}} = 0.151D_{10}$$

from which $D_{10} = 0.033$ cm or 0.33 mm (fine sand range)

b. For the 18-in. diam mold:

$V = 75{,}047.42 \text{ cm}^3$

$A = 7{,}078.16 \text{ cm}^2$

$V/A = 10.60 \text{ cm}$

$$.005 = \frac{1.6D_{10}}{6\,\frac{V}{A}} = 0.025D_{10}$$

$D_{10} = 0.199$ cm or 1.99 mm (coarse sand range)

Therefore, in the 4-in. diam mold, no correction would be required to the measured void ratio if the minus No. 4 material contained 10 percent or more finer than 0.33 mm. In the 18-in. diam mold no correction would be required if the total material contained 10 percent or more smaller than 1.99 mm. Practically speaking, these calculations show that for soils typically tested by impact compaction to obtain moisture-density curves that corrections to measured void ratio for rigid mold boundary effects would not be required since such materials typically contain more than 10 percent finer than the No. 200 sieve. This cannot be said for determination of maximum and minimum densities for cohesionless soils where material D_{10} sizes may be considerably larger.

114. To adapt Hardin's approach to estimate the rigid boundary effects produced around a rigid gravel particles buried within the minus No. 4 material, it is only necessary to envision the particles as a "molds" containing the finer fraction material. This approach then yields the specific volume of material requiring correction to be that contained within the "molds", i.e., the total volume of the gravel. Equation (1) is used to obtain the "measured" value of the dry unit weight of the minus No.4 fraction. Equation (9) can then be used to determine the correction which would be required to the measured void ratio of the volume of material contained within the particle-shaped "molds". If the particle is assumed to be spherical in shape, the ratio of its volume to its surface area, V/A, is 1/3 the radius such that the calculated correction increases as the particle size decreases. Thus, a most severe case for a given D_{10} of the fraction would be for a small spherical gravel size at a high gravel content. After determination of the correction required to the measured void ratio of the small volume of material contained within a single particle-sized spherical "mold", that volume can be represented as a uniform thickness of the material around the particle. Visualizing this physical concept for all of the gravel particles, the total volume of minus No. 4 material requiring correction is then identical to the total volume of gravel solids and, depending on the gravel content, may or may not constitute 100 percent of the total volume of the minus No. 4 fraction in the total material. It is to be noted that this approach assumes that the envisioned layers of material around the particles do not overlap. In fact, at some gravel content surely lower than the "optimum" gravel content, this assumption will not be true and will lead to an inflated value of percentage of total minus No. 4 volume requiring correction. For instance, in the case of uniform spherical particles, the assumption would no longer be true once the distance between particles becomes 0.26 times the particle diameter. Reference back to Figure 191 indicates that this particle separation would begin to occur at about 35 percent gravel content. In addition, particles near the specimen boundary which would result in only a portion of the envisioned layer being included in the corrected volume are also not accounted for. So, the approach to computing the percentage of total minus No. 4 volume requiring correction to the dry unit weight is conservative. Accepting the conservatism of the method, the total correction to the density of the minus No. 4 fraction can be computed using a weighting approach, i.e, using a

corrected dry unit weight for that portion of the minus No.4 found to require correction and the "measured" (calculated using Equation (1)) dry unit weight for the remainder.

115. To check a severe case of small gravel particles and high gravel content, the procedure described above will be followed assuming a gradation containing 50 percent gravel with uniform spherical particles passing the 3/8-in. sieve and a minus No. 4 fraction with a D_{10} of 0.074 mm (No. 200 sieve size). A value of 130 pcf will be assumed for the maximum dry unit weight of the total material, a value of 2.60 will be taken for the bulk specific gravity of the gravel and a value of 2.70 will be used for the specific gravity of the solids for the minus No. 4 fraction.

Calculation of the correction for one particle:

(1) Diameter of spherical particle passing 3/8-in. sieve = 9.52 mm

(2) V/A = 1/3 radius (r) = 4.76 mm/3 = 1.59 mm

(3) correction = $\frac{1.6D_{10}}{6V/A} = \frac{1.6\ (.074\ \text{mm})}{6\ (1.59\ \text{mm})} = 0.0124$

Equivalent uniform thickness of volume around a particle:

(1) $\frac{4r_1^3}{3} = 2V = 903.52 mm^3$

(2) $r_1^3 = 215.70\ \text{mm}^3$

(3) $r_1 = 6.00$ mm

(4) equivalent uniform layer thickness = $r_1 - r = 1.24$ mm

This step is not necessary to the ultimate objective and is only shown to aid the reader's visualization of the concept.

Total volume of minus No.4 material requiring correction:

As previously explained, this volume is equal to that of the gravel or 11,340 cc. Following the physical concept, this is equal to the volume of material around each particle requiring correction times the total number of gravel particles.

Total volume of minus No.4 material in the total material:

(1) This volume is equal to the total volume of 1.0 cu ft minus the volume of the gravel or 28,317 cc - 11,340 = 16,977 cc

(2) Therefore, the percentage of the total volume of minus No.4 material requiring correction is $\frac{11{,}340\text{cc}}{16{,}977\text{cc}}$ = 67 percent.

Void ratio and dry unit weight of the minus No.4 fraction

(1) Uncorrected or "measured" dry unit weight of minus No. 4 fraction calculated from Equation (1) = 108.45 pcf or void ratio = 0.554 (G_s taken as 2.70)

(2) Corrected void ratio for 67 percent of the fraction = 0.554 - 0.012 = 0.542

(3) Corrected dry unit weight of 67 percent of minus No. 4 fraction = 109.3 pcf

(4) Weighted value of corrected dry unit weight of minus No. 4 fraction:

0.67(109.3 pcf) + 0.33(108.45 pcf) = 109.0 pcf

So, for a material containing 50 percent by weight of uniform spherical 3/8-in. gravel particles and a minus No. 4 fraction with a D_{10} = 0.074 mm, the density of the minus No. 4 material in the total material would require correction upward of 0.6 pcf relative to that calculated using Equation (1) to account for this relatively severe case of rigid particle boundary effects. If the above computations are carried out changing only the gravel to uniform spheres passing the 1-1/2-in. sieve, the void ratio correction becomes 0.003, the percentage of the minus No. 4 fraction requiring correction remains the same and the weighted value of corrected density of the minus No. 4 fraction increases by less than 0.2 pcf over that calculated using Equation (1). At 50 percent gravel the particle separation indicated by Figure 191 would be so small that the conceptual uniform layers around particles used in calculation of the total percent of the minus No. 4 volume requiring correction would overlap significantly. Therefore, the already minor corrections to dry unit weight indicated for the two particle sizes treated above would be excessive.

116. Figure 192 is provided as a summary of the void ratio correction indicated by Equation (9) for various sizes of uniformly graded spherical gravel particles. The minus 3-in. gradation tested by the USBR (1963) shown in Figure 1 contained 50 percent gravel and had an average gravel particle size of about 1-1/2-in. and the minus 3/8-in. gradation (Figure 1) contained only 18 percent gravel. The minus No. 4 fractions exhibited a D_{10} of less than 0.005. A quick assessment using Figure 191 reveals that none of the materials tested by the USBR would have required a significant dry unit weight correction to that calculated from Equation (1) for the minus No. 4 fraction for particle rigid boundary effects. Gordon, Hammond and Miller (1965) tested

the gradations shown in Figure 10. The smallest maximum particle size for gravelly gradations was 3/4-in. at a maximum gravel content of about 35 percent. The largest maximum particle size was 4-in. at a maximum gravel content of about 60 percent. The D_{10} of the minus No. 4 materials was about 0.002 mm. None of their test data would require significant correction of the calculated dry unit weight of the minus No. 4 fraction. The full-scale Degray Dam gravel tested by Donaghe and Townsend (1973) shown in Figure 15 contained 47 percent gravel with an average particle size of about 3/4-in. and a minus No. 4 fraction with a D_{10} less than 0.001 mm. For this material, there would be no significant correction of the calculated dry unit weight of the minus No. 4 fraction. The same is true for the scalped/replaced minus 3/4-in. gradation of the DeGray Dam material. Donaghe and Townsend (1975) also tested the gradations shown in Figure 19. Gravel content of full-scale and companion minus 3/4-in. scalped/replaced gradations ranged up to 60 percent. The D_{10} of the minus No. 4 material was apparently around 0.005 mm. Considering the worst case of the minus 3/4-in. scalped/replaced gradation with 60 percent gravel, no significant correction to the calculated void ratio of the minus No. 4 fraction is computed from Equation (9). Garga and Madureiras' test gradations listed in Table 18 show that the minus No.4 materials exhibited between 13 and 33 percent smaller than the 2 micron (0.002 mm)particle size. Figure 192 shows that for any of the maximum particle sizes tested that the void ratio of the minus No.4 fractions would not be corrected as much as 0.001. Figures 66 and 67 show the gradations tested in this investigation. The minus No. 4 fractions (Gradations 1C and 3C) with both silt and clay fines ranged in D_{10} between about 0.01 mm and 0.0005 mm. None of these gradations would require a significant correction to the calculated dry unit weight of the minus No. 4 fraction in the total material.

117. It is concluded that a typical earth-rock mixture containing 10 percent or more fines would not require either correction of the maximum dry unit weight of the total material for rigid boundary effects of the compaction mold or correction of the calculated dry unit weight of the minus No. 4 fraction for rigid boundary effects of the gravel particles. In addition, where compaction tests of the minus No.4 fraction are performed in a 4-in. diam mold, no correction is required to that dry unit weight for rigid compaction mold boundary effects. Therefore, the argument that the calculated (Equation 1) decline in dry unit weight of the minus No. 4 fraction of the

total material with increasing gravel content is significantly attributable to improper inclusion of voids due to rigid boundary effects of the gravel particles is not sustained.

118. A third hypothesis of gravel interference is that the presence of the gravel alters the manner in which the fraction "feels" the applied compactive effort. Generally, this has been seen as a shielding of the fraction from the full effects of the applied energy at moderate (say, 35 percen and higher gravel contents. The most extreme effects would, of course, become evident at the gravel content (usually greater than 50 percent) at which the gravel particles begin to come into contact. Above that gravel content, the hypothesis of interference as the development of unfilled voids between gravel particles becomes more apropos. However, it is not this extreme situation at higher gravel content which is ordinarily of practical interest in the compaction/compaction control of earth-rock mixtures. Instead, it is more important to understand the effects of gravel on the densification of the finer fraction as gravel content increases toward the onset of the severest interference conditions which can likely be taken as the "optimum" gravel content with respect to the maximum dry unit weight for a given compactive effort.

Relative Compaction of a Fraction of the Total Material

119. Unlike past investigations, the testing program reported herein provides the necessary comparative data to track the compacted state of the minus No. 4 and minus 3/4-in. fractions with gravel content against their own compaction curves. This is to say that for a given total material at its optimum water content and maximum dry unit weight, the calculated water content (Equation (2)) and dry unit weight (Equation (1)) of the fraction can be compared directly with the compaction curve for the fraction to assess the influence of the gravel. In the absence of specific test information, calculation of the water content of the minus No.4 fraction from Equation (2) has to be made by taking the optimum water content of the total material and the air-dry water content (0.6 percent) of the gravel since the wetted fraction was added to air-dry gravel immediately before compaction. There is no reason to believe that the water content of the gravel remained precisely as-mixed but the authors are of the opinion that the gravel did not rob sufficient

water from the fraction during the time compaction was performed to invalidate the comparative study. An additional necessary consideration for such comparisons is that the compaction curve for the fraction be that obtained in the same size mold as for the total material. As will be evident later, when the total material is at its optimum water content, the fraction is not (except for a singular value of gravel content) so that the fraction would not achieve its maximum dry unit weight under the applied compactive effort unless the gravel produces an extraordinary net densification (a "positive" interference). If the fraction achieves its standard effort dry unit weight at its water content in the total material, then no interference by the gravel is indicated. If the fraction attains a net dry unit weight in excess of its standard effort dry unit weight at its water content in the total material, a "positive" interference is implied. If the gravel produces a net "shielding" of the fraction from the full effects of the applied effort, the dry unit weight achieved by the fraction will not reach the value of its standard effort dry unit weight at its water content in the total material (a "negative" interference). Of course, there is nothing to say for all these cases that both "positive" and "negative" interference effects can't be coexistent (and probably are). Note that reference has been made to the net dry unit weight of the fraction because it is reasonable to believe that the density pattern within the fraction is very variable.

120. Figure 199 presents the results of the comparisons described above expressed as the percentage of standard effort dry unit weight attained by the minus No. 4 fractions at their water contents in the total material versus the gravel content of the total material. Figure 199 is a plot of the same percentages as a function of the percent minus No. 200 sieve size in the total material. Ignoring the estimated trend curves (to be discussed later) shown in Figure 199, it would appear that the data for gradations with silt fines and for those with clay fines represent single respective trends across the range of gravel contents even though minus No.4 fractions of Gradations 1 and 2 and their fractions and Gradations 3 and 4 and their fractions were different (see Table 19). However, when the data are plotted against percent minus No. 200 sieve size as in Figure 199, it is seen that the different minus No. 4 fractions produced different data trends especially for clay fines even though no practical difference is evident for Gradations 1 and 2 and their fractions on the basis of plasticity of fines. Figure 199 indicates that, in

general, the addition of gravel to a minus No.4 material (whether plastic or nonplastic) will result in a decreasing trend in the compaction of the fraction with respect to its standard effort dry unit weight for its water content as a component of the total material. Initially, over some lower range in gravel content which varies with gradation and/or plasticity of the fraction, the dry unit weight of the fraction will exceed its standard effort dry unit weight for its water content and at higher gravel contents will fail to reach that value. Apparently, the fraction will be brought to its standard effort dry unit weight for its water content only at some singular value of gravel content. Figure 199 shows the converse as a reversed trend with increasing fines content (minus No. 200 sieve size). It is very difficult to explain the trends of Figures 199 and 200 on the basis of gradation and plasticity factors because of the number of variables involved and the fact that two minus 3/4-in. and minus No. 4 fraction gradations were employed. Both figures show the data to be indistinguishable on the basis of plasticity of fines for Gradations 1 and 2 and their gravelly fractions. On the other hand, the data for Gradations 3 and 4 and their gravelly fractions distinctly separate on the basis of plasticity of fines. Why would gradations 1,1A,2,2A and 1B with percent fines ranging from 21 to 35 percent not result in separate trends for silt versus clay fines while Gradations 3,3A,4,4A and 3B with percent fines over the identical range do? The gravel contents ranged from 10 to 46 percent for Gradations 1,1A,2,2A and 1B and from 40 to 64 percent for Gradations 3, 3A,4,4A and 3B. With the same range in fines content but a generally higher percent gravel, the ratio of sand content to fines content was lower for Gradations 3 and 4 (0.71) and their gravelly fractions than for Gradations 1 and 2 and their fractions (1.57). Certainly, for the case of clay fines this translates to a more plastic nature of the minus No.4 fraction of Gradations 3 and 4 and their fractions as compared to Gradations 1 and 2 and their fractions. The authors guess that the higher ratio of sand to clay fines (1.57) in Gradations 1 and 2 and their gravelly fractions produced a sufficiently low plasticity of the minus No. 4 fractions that differences in relative compaction of those fractions as compared to those containing silt could not be seen within testing precision variations. In the case of Gradations 3 and 4 and their gravelly fractions with a lower sand to clay ratio (0.71), the plasticities of the minus No. 4 fractions were sufficiently different between silt and clay fines to see a difference in the data trends. However, in the range of overlap in gravel contents between the two gradation data sets (Figure 199) which is between 40 and 46 percent, the data for silt fines approximately correspond. This leads to the thinking that the trend separation for silt fines of Figure 194 is not explained by a difference in sand to silt ratio but is surmised to be the result of the difference in gravel contents of the two minus 3/4-in. fractions. For clay fines in the overlap range of gravel content, the data for Gradations 3 and 4 and their fractions fall significantly lower than for Gradations 1 and 2 which is seen as the combined effects of plasticity and gravel content. The estimated trend curves drawn on Figures 193 and 195 are based on the above reasoning. Note that the authors take the liberty in Figure 193 to indicate by pure supposition (dotted curve) that the trend curve for Gradations 1 and 2 and their fractions (not shown, but also for Gradations 3 and 4 and their fractions) must pass through zero gravel content at 100 percent of the fractions' standard effort densities which would correspond to their maximum dry unit weights. So, in summary and almost obviously, for a given gravel content, the relative state of compaction achieved by the minus No. 4 fraction is a function of gravel content and plasticity such that increasing gravel content and/or plasticity of the finer fraction results in a decreasing percent of standard effort density of the fraction.

121. Figure 195 shows the calculated water contents of the minus No. 4 fractions with respect to their optimum water contents versus gravel content in the total material. Figure 196 plots the same relative water contents versus percent fines in the total gradation. It is evident from these two figures that the relative water content data scatter significantly but the authors still venture to affix estimated trends. Viewing the data holistically, Figure 195 shows that as gravel content is increased from a low value, the fraction has to be steadily wetted from dry of its optimum to increasingly wet of its optimum to permit the total material to come to its maximum dry unit weight for the applied compactive effort. Unlike the relative compaction data for Figures 193 and 195, the relative water contents for Gradations 1 and 2 and their fractions do separate on the basis of plasticity of fines. Just as the percentages of standard effort dry unit weight for their water contents are similar between silt and clay fines (Figures 193 and 195) in Gradations 1 and 2 and their fractions so also are their percents of maximum dry unit weight. Therefore, the corresponding water contents relative to optimum

cannot be similar because of the typical differences in shapes of compaction curves between plastic and nonplastic materials, i.e., the dry and wet legs of compaction curves of silty materials are generally steeper in slope than for plastic soils. Figure 196 is more or less a mirror image of Figure 195 but with a more distinct separation of data because of the two minus 3/4-in. fractions employed in the gradations and because, for a given percent fines, Gradations 3 and 4 and their fractions contained more gravel than Gradations 1 and 2 and their fractions. Again, the authors show in Figure 195 that the water contents of the fractions must trend to their optimum water contents at zero percent gravel.

122. Figures 197 and 198 present relative compaction and relative water content data for the minus 3/4-in. fractions, respectively. The relative compaction data of Figure 197 do not appear to be separable by plasticity of the minus No. 200 material within the precision of the results but certainly can be distinguished on the basis of the two different minus 3/4-in. fractions employed in the test gradations. The minus 3/4-in. fractions (Gradation 1B) of Gradations 1, 1A, 2 and 2A contained only 10 percent gravel while the minus 3/4-in. fractions (Gradation 3B) of Gradations 3, 3A, 4, and 4A contained 40 percent gravel. It appears that the data for Gradations 3 and 4 and their minus 2-in. fractions were shifted downward as a result of the higher gravel content. The relative water content data of Figure 198 also show that the minus 3/4-in fractions had to be wetted as additional gravel was incorporated to produce the optimum water content of the total material. The data are sufficiently scattered in Figure 198 that the authors prefer not to draw estimated trend curves even though it appears that Gradations 1 and 2 and their fractions trended lower and flatter as compared to Gradations 3 and 4 and their fractions. The data probably should be separate on the basis of plasticity of fines but the presence of gravel in the fraction apparently made the compaction curves less distinctive in shape by plasticity of fines as compared to the minus No. 4 fractions.

123. The relative compaction and relative water content data for the minus No. 4 fractions and the minus 3/4-in. fractions can be combined as in Figure 199 and 200, respectively, by taking the abscissa of the plots as percent oversize. When this is done, it is seen from Figure 199 for relative compaction that the two data sets are compatible. The estimated trend curves shown in Figure 199 offer a revision of trends previously affixed to

Figure 195 where a separation between Gradations 3 and 4 and their fractions on the basis of plasticity of fines could be interpreted. The relative water content data of Figure 200 are so scattered and mixed among plasticity of fines and gradations that the authors do not attempt to show separate trends.

Implications of the Test Data Regarding the Nature of Gravel Interference

124. The test data presented above show that the minus No. 4 fractions transition in their net dry unit weights in the total material with increasing gravel content from values which exceed their standard effort dry unit weight for their water content ("positive" gravel interference) to values which fail to equal that dry unit weight ("negative" gravel interference). The range in lower values of gravel content over which the fraction is subject to "positive" interference apparently varies with gradation and the overall plasticity of the fraction. However, "positive" interference is also seen for some range in lower gravel contents for nonplastic fractions. The USBR (1989) confirms this effect in terms of percent compaction of the minus No. 4 fraction (see Figure 190) for clayey gravels but not for silty gravels. Nothing specific can be said for gravel contents lower than 10 percent since that was the lowest gravel content tested in this investigation other than that the trend in relative compaction of the fraction (see Figure 199) must return to 100 percent of maximum dry unit weight of the minus No. 4 fraction at zero percent gravel.

125. Figure 201 presents a grossly simplified picture representing only one possible effect explaining how the presence of small quantities of gravel can result in a net dry unit weight of the fraction which is in excess of its standard effort dry unit weight for its water content in the total material. The discussion of the simplified picture to follow obviously ignores the fact that shearing of the fraction also takes place as the gravel particles are forced closer together. That shearing may produce either a volume increase or volume decrease in the affected zone of the fraction assuming drained conditions. In addition, it seems logical that the shape of the gravel particles themselves would generate density patterns about them after the fashion of variously shaped objects placed in a stream of flowing viscous fluid. The authors would not dare to address the effects of shear and particle shape and

proceed under the contention that the effect described below is at least as significant as other effects and possibly dominant.

126. From Figure 201, for any given uniform deformation of the specimen, ΔH, the average dry unit weight of the fraction within some region A between the two rigid particles will be higher than that in region B, having been subjected to a greater volumetric strain. Consequently, the fractional material in region A will also become stiffer as long as its degree of saturation has not been pushed too high. It is also evident that for the given uniform change in height, ΔH, the degree of extra densification and stiffening of the material between the particles will be a function of the initial distance between the particles. In an earth-rock mixture, the initial distance between particles is a direct function of gravel content after the theoretical fashion of Figure 191. The test data analyses presented above show that as long as the gravel content is sufficiently low, the applied compactive effort can successfully move the gravel particles against the stiffening of the material between them and also densify the material outside those regions such that the minus No. 4 fraction can be brought to an overall net dry unit weight which exceeds that to which the material could be brought at its water content in the absence of the gravel and "positive" interference is calculated. However, as gravel content is gradually increased and, consequently, initial distance between the gravel particles decreases, the applied effort is less and less capable of moving the particles against the more rapidly increasing stiffness of the material between them and the stiffer material begins to dominate the absorption/reflection of the applied energy. As this condition develops, the material not directly between particles begins to be partially shielded from the applied energy. At some gravel content, the shielded portion of the fraction becomes so lightly densified that the net dry unit weight of the fraction fails to equal that value to which the compactive effort would bring the fraction at its water content if the gravel were absent and "negative" interference is calculated. As the gravel content reaches its "optimum" value, the gravel particles almost immediately come into contact and essentially the entire fraction becomes unaffected by the continued application of energy unless gravel particle breakage ensues.

127. It was also shown that the minus 3/4-in. fractions exhibit trends in relative compacted dry unit weights which are similar to those seen for the minus No. 4 fractions. Of course, the argument of stiffening material between

gravel particles can't be specifically extended to the minus 3/4-in. fractions. However, the authors submit that the minus 3/4-in. fraction results are only a manifestation of trends in the minus No. 4 materials. For that matter, the minus No. 4 fraction trends may also actually be a reflection of the behavior of a still smaller fraction but still in the manner as hypothesized above.

A Unified View of the Effects of Gravel on the Compaction of the Minus No.4 or Minus 3/4-in. Fraction

Maximum dry unit weight

128. The USBR and AASHTO approach to predicting the maximum dry unit weight of the total material employing Equation (5) was previously discussed beginning with paragraph 67. Equation (5) includes the "r" factor or Fraction Density Factor which is the decimal expression of the percent compaction of the minus No. 4 fraction in the total material based on the dry unit weight calculated for the fraction from Equation (1) when the total material is at its maximum dry unit weight. The Fraction Density Factor was expressed as a function of gravel content (see Figure 183). It was shown (see Figure 189) that the Fraction Density Factor versus gravel content relationships resulting from this study and those of other cited investigators varied over such a significantly wide range that use of single curves such as those recommended by the USBR or AASHTO could result in unacceptably inaccurate predictions of maximum dry unit weight of the total material using Equation (5). It was also shown (see Figure 190) that the calculated value of maximum dry unit weight of the total material is very sensitive to small differences in the Fraction Density Factor.

129. Equation (5) interrelates the percent compaction of the fraction, the maximum dry unit weight of the total material, the percent gravel or percent fines and the bulk specific gravity of the gravel. The value of percent compaction of the minus No.4 or minus 3/4-in. fraction (Fraction Density Factor) can be normalized by division by the percent gravel in the total material times the bulk specific gravity. The authors choose to call this parameter the "Density Interference Coefficient", I_c, which is defined as follows:

$$I_c = \frac{r}{P_g G_m} \tag{10}$$

where

- r - Fraction Density Factor which is decimal value of percent compaction of the minus 3/4-in. or minus No. 4 fraction when total material is at maximum dry density
- P_g - decimal value of percent gravel in total material
- G_m - bulk specific gravity of the gravel

Smooth curves of this parameter versus gravel content are obtained as shown in Figure 202 for both corrected and uncorrected data and for both silt and clay fines obtained from this investigation. The calculated values shown in Figure 202 are summarized in Tables 53 and 54. Figure 203 shows similar results if the percent compaction of the minus 3/4-in. fraction is treated in the same manner. Tables 55 and 56 present those discrete data. Figure 204 confirms similar results for the minus No. 4 fraction data of Garga and Madureira (1985), Figure 205 for the minus No. 4 fraction data of Donaghe and Townsend (1975) and the USBR (1963) and Figure 206 for the results reported by Gordon, Hammond and Miller (1964). The discrete data plotted in Figures 204 through 206 are given in Tables 57 through 59. It is gratifying to realize from Figures 202 through 206 that a smooth curve can indeed be fitted to each data set even though whole families of gradation curves are represented, including not only variable gravel content but also variable percent fines and variable maximum particle size. The apparent smooth trend in the Density Interference Coefficient is tantamount to a single "line of optimums" in the plot space of maximum dry unit weight versus optimum water content. It is pointed out that other compaction control methods such as the one or two point compaction test of EM 1110-2-1911, Appendix B, rely on the concept of a family of compaction curves conforming to a single line of optimums. All other things being identical, the authors reason that a difference only in bulk specific gravity of the gravel would perhaps shift a given value of maximum dry unit weight but not the optimum water content. Therefore, the bulk specific gravity is utilized in the calculation of the Density Interference Coefficient because it appeared in study of available data that its use might reduce the coefficient to a single curve for gravelly soils from one geological environment but exhibiting variable bulk gravities. This remains to be verified. The Garga and Madureira (1985) data of Figure 204 represents a range in maximum particle size, linear gravel gradations and variable minus No. 4 fractions as described in Figure 38 and Table 18. Figure 204 shows some separation of the trends by compactive effort which appears trivial but, just as for the Fraction Density Factor, a back-calculation of maximum dry unit weight of the total material is also sensitive to very small changes in the Density Interference Coefficient. The minus 3-in. and minus 3/4-in. scalped/replaced data of Donaghe and Townsend (1975) of Figure 205 represent the range in gradations shown in Figure 19. It is important to see in Figure 205 that the scalped and replaced gradations produced a different curve as compared to that indicated for the minus 3-in. parent gradations. This is additional evidence that scalping/replacing in effect generates a different genre of materials. It is also seen in Figure 205 that data obtained by Donaghe and Townsend on minus 3-in. and minus 3/4-in. scalped/replaced gradations containing 40 percent gravel and variable fines (see Figures 33 through 35) also fell on the respective curves for the major test program for which the percent fines was fixed at 25 percent (see Figure 19). The USBR (1963) data of Figure 205 represents the minus 3-in. to minus 3/8-in. gradations of Figure 1a. It appears that for a range in gradations of gravelly soils as would generally be obtained from geologically similar project borrow sources that a single smooth curve of Density Interference Coefficient, I_c, versus gravel content in the total material can be developed for either the minus No. 4 or minus 3/4-in. fractions. Density Interference Coefficients developed by treating fractions of those gradations as full-scale materials will lie on the same curve as those for the parent gradations but coefficients developed for derivative scalped and replaced gradations will not.

130. Density Interference Coefficients based on maximum dry unit weights obtained in small molds on the minus No. 4 or minus 3/4-in. fractions will also conform to a smooth curve versus gravel content in the total material. This is shown as data uncorrected for equipment size effects in Figures 202 and 203 for this investigation. Coefficients calculated for Garga and Madureira of Figure 204 are uncorrected data as are those for Donaghe and Townsend of Figure 205 and Gordon, Hammond and Miller of Figure 206. However, the USBR data of Figure 205 includes both corrected and uncorrected results. It was previously pointed out in the literature review that the USBR and Donaghe and Townsend had seen significant equipment size effects between

values of maximum dry unit weight of the minus No.4 fraction obtained in the 4-in. diam mold as compared to the large mold (18 to 19-in. in diameter). The USBR data of Figure 205 shows a significant shift in the Density Interference Coefficient as a result of the equipment size effects.

Predicting the maximum dry unit weight of the total material using density Interference Coefficients

131. Because the value of maximum dry unit weight of the total material back-calculated on the basis of the Density Interference Coefficient is sensitive to small variations in the factor as indicated in Figure 207, it is necessary to assess the practicality of use of the curve for prediction purposes. In other words, if a smooth curve is fitted by eye to the Density Interference Coefficient versus gravel content data, will values picked off that curve result in a satisfactorily accurate prediction of the maximum dry unit weight of the total material? The prediction procedure amounts to calculating the percent compaction of the fraction in the total material from the Density Interference Coefficient (given the gravel content and the bulk specific gravity) and then translating that value to actual dry unit weight of the fraction by multiplying the percent compaction of the fraction by its maximum dry unit weight. The correct dry unit weight of the fraction can then be entered into Equation (1a) to calculate the maximum dry unit weight of the total material. Equation (1a) can be restated in terms of the Density Interference Coefficient, I_c, beginning with previously stated Equation (10) as follows:

$$I_c = \frac{r}{P_g G_m} \qquad (10)$$

and, since $r = \frac{\gamma_f}{\gamma_{fmax}}$ wherein γ_{fmax} is the maximum dry unit weight of the finer fraction

$$\gamma_f = P_g I_c \gamma_{fmax} G_m$$

substituting into Equation (1):

$$\gamma_{tmax} = \frac{P_g I_c \gamma_{fmax} \gamma_w G_m}{f\gamma_w + P_g C I_c \gamma_{fmax}} \tag{11}$$

where

γ_{tmax} = predicted maximum dry unit weight of the total material, pcf

γ_w = unit weight of water or 62.4 pcf

f = decimal value of percent finer fraction by weight

c = decimal value of percent oversize by weight which is equal P_g if I_c is based on the minus No. 4 fraction

If the bulk specific gravity of the gravels associated with a project is not a variable, it need not be used in the calculation of the Density Interference Coefficient. Equations (10) and (11) above would be altered accordingly. The only effect would be a scaling upward of the numerical values of the coefficient and the absence of the bulk gravity in back-calculation of the maximum dry unit weight of the total material using the coefficient to be presented in the next paragraph. It is emphasized that there must be no presumption that the bulk gravities of the gravel fractions are all the same since the breakdown of the parent geological materials into different sizes to form the gradation at hand may well reflect mineralogy. It would be wise to verify these numbers by testing each gravel fraction.

132. Figure 208 presents the results of prediction of the maximum dry unit weight of the total material using Equation (11) with the Density Interference Coefficient based on the minus No.4 fractions of the gradations tested in this study. Figure 209 presents the prediction results using a Density Interference Coefficient based on the minus 3/4-in. fraction. For both the corrected and uncorrected data, a Density Interference Coefficient versus gravel content curve was drawn through the average values of Figures 202 and 203 taking the silt and clay fines data together as one set. To do this, it was found necessary to plot the data of Figures 202 and 203 to a sufficiently large scale to allow picking of values from the curve with a good estimate of the third decimal place in the value of Density Interference Coefficient. For sake of simplicity, the two percent precision limits shown in Figures 208 and 209 (and in similar figures to follow) were calculated by taking two percent of the actual value of maximum dry unit weight of the total material. The rigorously correct way to apply the precision limit would be to average each pair of actual and predicted values and then take two percent of

that number. However, the simplified approach does not result in any comparative data points falling within the approximate precision limits shown when in fact they are actually without by the correct calculation. Figures 208 and 209 both show that for the materials tested in this investigation that average Density Interference Coefficients based on either the minus No. 4 or minus 3/4-in. fractions will result in excellent predictions of maximum dry unit weight of the total material for gradations containing either silt or clay fines. The authors emphasize that this finding only applies to the materials tested for this study. Other materials may differ significantly on the basis of plasticity of fines.

133. Figure 210 presents results of predictions of maximum dry unit weight of the total materials using the data reported by Garga and Madureira (1985). In this case, separate Density Interference Coefficient (based on the minus No. 4 fractions) versus gravel content curves were used for each data set by compactive effort. This was required because the very small shifts in the data seen in Figure 204 with compactive effort were significant. Figure 210 shows that, in general, the predictions of maximum dry unit weights of the total materials fell within a two percent precision range of the actual values.

134. It would not be a significant exercise to predict maximum dry unit weights of the total materials using the data of Donaghe and Townsend (1975) or USBR (1963) because only one set of gradations were used in those studies. Therefore, a smooth Density Interference Coefficient versus gravel cor. ent curve could be precisely fitted through those respective data and exact replication of actual maximum dry unit weights of the total materials would result.

135. Figure 211 presents the results of predictions of maximum dry unit weights for the total materials using the data reported by Gordon, Hammond and Miller (1964). Again, the Density Interference Coefficient (based on the minus No. 4 fractions) versus gravel content curve was fitted by eye to the data of Figure 206 as indicated in the figure. The prediction method for these data was complicated by the fact that fractions of the gravel components of those materials had different bulk specific gravities (see Table 11) which ranged from 2.67 for the smaller sizes up to 2.85 for the larger sizes. Generic rather than exact gradations of the test specimens were provided so that only crude weighted values of bulk specific gravity could be calculated using the percentages by weight of each gravel size range in the generic gra-

dations. Even though Figure 211 shows excellent results in prediction of maximum dry unit weights of the total materials, the authors believe the results would have been better if the bulk specific gravity had been available for each tested gradation's gravel fraction taken as a whole.

136. Because the Density Interference Coefficients calculated for several of the clayey gravels tested by several previous investigators appeared to correspond with those obtained from this investigation, it was decided to lump those data together as in Figure 212 and again predict the maximum dry unit weights of the total materials. Figure 213 shows relatively good predictions of maximum dry unit weights of the total materials using the Density Interference Coefficient curve shown in Figure 212. It is to be noted that the data of Gordon, Hammond and Miller which was also for a clayey gravel compacted at standard effort, are not included in Figures 212 and 213. It was found that their Density Interference Coefficients generally trended significantly lower than all the other investigators. This is not a criticism of their data but rather an indicator that, just as for fraction density factors, it should not be presumed that there is one general Density Interference Coefficient curve for all clayey gravels. In fact, if the data of Figure 213 are examined closely, subtle differences in Density Interference Coefficients are indicated for each data set by their groupings.

137. It is important to realize from the previously presented predictions of maximum dry unit weight of the total material that the Density Interference Coefficient compensates for equipment size effects because its value is dependent upon the value of the maximum dry unit weight of the fraction which is itself dependent on the mold size in which it was determined. This is to say that the Density Interference Coefficient must not only be considered as associated with a particular fraction, i.e., the minus No. 4 or minus 3/4-in., but also must be viewed as associated with the particular mold size in which the maximum dry unit weight of that fraction was determined. It is possible to illustrate the error resulting from mismatching the Inteference Coefficient and the maximum dry unit weight of the fraction by taking the USBR corrected Density Interference Coefficients of Figure 205 and using them with the maximum dry unit weight determined in the 4-in. diam mold (uncorrected data). It is recalled from review of the literature (see PART III) that the USBR reported a difference in maximum dry unit weights for the minus No. 4 fraction between the 4-in. and 20-in. diam molds of 9.1 pcf (the larger mold

giving the higher value). Figure 214 shows that use of the 4-in. mold maximum dry unit weight for the minus No. 4 fraction with the corrected Density Interference Coefficients results in underprediction of the actual maximum dry unit weights of the total materials. The magnitude of the underprediction varies inversely with gravel content having a value of 6.4 pcf at a gravel content of 16.7 percent (minus 3/8-in. gradation) and a value of 8.0 pcf at a gravel content of 50 percent (minus 3-in. gradation). However, if USBR uncorrected Density Interference Coefficients of Figure 205 are correctly paired with the maximum dry unit weights of the fraction determined in the 4-in. diam mold, the predicted maximum dry unit weights of the total materials match the actual values as also shown in Figure 214.

Developing Density Interference
coefficients without large-scale
compaction tests on the total material

138. In practice, very few agencies, consultants or contractors have the capability to perform compaction tests on total materials in large molds. It was previously demonstrated that Density Interference Coefficients determined on fractions of the total material treated as total materials in their own right fall on the same curve versus gravel content as the parent total materials. The general shape of the Density Interference Coefficient versus gravel content curve suggests that it might plot as a straight line in log-log coordinates. Figure 215 presents the data of Figure 212 replotted in this manner with the addition of the Gordon, Hammond and Miller data of Figure 206. It is seen from Figure 215 that the data trends are linear for all investigators between 10 and about 45 percent gravel. Above about 45 percent gravel, the data trends are no longer linear in the log-log space but seem to become linear and parallel in cartesian coordinates as shown in Figure 216. The apparent linearity between 10 and 45 percent gravel in log-log coordinates offers the strong possibility that fractions of the total materials compacted in smaller molds may be used to establish the Density Interference Coefficient versus gravel content curve for gravel contents in the total materials up to 45 percent. The linearity in cartesian coordinates above about 45 percent gravel is of little use unless a fraction conforming to available mold sizes contains that much gravel. Establishment of the Density Interference Coefficients using fractions and small molds could be achieved as follows:

a. Select representative total material gradations which span the range encountered in the borrow source. As a precaution, treat separate borrow sources separately.

b. Obtain representative samples of the minus 1-in. or minus 3/4-in. fractions and representative samples of the minus No. 4 fractions.

c. Determine the gravel contents and bulk specific gravities of the minus 1-in. or minus 3/4-in. fractions.

d. In the 6-in. diam mold, perform compaction tests on the minus 1-in. or minus 3/4-in. fractions and on the minus No. 4 fractions to determine the maximum dry unit weights for each.

e. Treating the minus 1-in. or minus 3/4-in. fractions as if they were total materials, i.e., using their gravel contents, and taking their bulk specific gravities, the computed dry unit weight of the corresponding minus No. 4 fractions at the maximum dry unit weight of the total material (Equation (1)), and the maximum dry unit weights of the corresponding minus No. 4 fractions, calculate the respective Density Interference Coefficients by Equation (10).

f. In log-log coordinates, plot the Density Interference Coefficients versus the respective gravel contents of the minus 1-in. or minus 3/4-in. fractions and carefully fit a straight line through the data points from 10 percent up to 45 percent gravel. Do not presume the linear fit to be good below 10 percent gravel. The data below 10 percent gravel should not be linear and would have to be determined by testing minus 1-in. or minus 3/4-in. fractions with gravel contents less than 10 percent.

g. Convert and plot the log-log straight line to cartesian coordinates at a scale permitting estimation of the Density Interference Coefficient to the third decimal place.

h. The cartesian coordinate curve of Density Interference Coeffiient versus gravel content should be acceptable for predicting the maximum dry unit weight of the total materials from the borrow source containing up to 45 percent gravel using Equation (9). If a minus 1-in. or minus 3/4-in. fraction happens to contain 50 percent or more gravel, the linear higher gravel content portion of the curve can be fitted through that data using a slope of 0.0132. Join the two curve segments together by drawing a smooth curve between 45 and 50 percent gravel.

It must be realized that the above procedure will not account for different values of maximum dry unit weight of total materials which might be obtained from the variety of large-scale compaction equipment which has been employed. In other words, if the same laboratory tested the same total materials using two differently configured pieces of large-scale compaction equipment, it would not be surprising if different maximum dry unit weights were obtained. This is not a question of precision of the test where all things are supposedly equal with respect to equipment and procedure. In the case of two differently constructed pieces of equipment, the above procedure may yield two different curves of Density Interference Coefficient but the proper curve employed with the data from the corresponding equipment would still correctly predict values obtained with that equipment. The authors are willing to venture the opinion that in the absence of a standard compaction test for soils containing large particles, that the values predicted by the above procedure would be as "good" as any obtained from some large-scale compaction test. This is reinforced by the observation that Density Interference Coefficients based on minus No. 4 fractions for minus 3/4-in. fractions tested in small molds fall on the same curve with those for the total materials tested in the large molds. Obviously, should the capability to perform large scale tests be available, the Density Interference Coefficients should be calculated using maximum dry unit weights of the total materials obtained in the appropriate large mold. Also note that the authors suggest that the minus 1-in. fraction may be used in the short-cut procedure described above in order to gain the maximum gravel content in the fraction. The current edition of EM 1110-2-1906, "Laboratory Soils Testing," does not allow the testing of a material containing a maximum particle size of 1-in. in the 6-in. diam mold.

<u>Optimum water content</u>

139. In a manner somewhat analogous to the Density Interference Coefficient, I_c, the optimum water contents of fractions and corresponding total materials can be used to calculate a simple factor which tracks the influence of gravel content as follows:

$$F_{opt} = \frac{\dfrac{W_{optf}}{W_{optt}}}{P_g} \tag{12}$$

where

F_{opt} = optimum water content factor

W_{optf} = optimum water content of the finer fraction, percent

W_{optt} = optimum water content of the total material, percent

P_g = decimal value of percent gravel in the total material

Figures 217 and 218 present the Optimum Water Content Factors, F_{opt}, based on the minus No.4 and minus 3/4-in. fractions calculated for the uncorrected compaction data plotted versus gravel content in the total materials.

Tables 60 and 61, respectively, present the calculations. Only the uncorrected factors are given in these two figures because the corrected values are not significantly different. As was the case for the Density Interference Coefficients, the Optimum Water Content Factors also yield a smooth curve with gravel content. Also, both Figures 217 and 218 show that the factors based on the minus No. 4 fraction and those based on the minus 3/4-in. fraction represent separate data sets. This is attributed to the significant shift in the compaction parameters with addition of small quantities of gravel to a minus No. 4 material as previously pointed out in discussion of maximum permissible degrees of scalping. Figures 219 and 220 present the data of Figures 217 and 218 plotted in log-log coordinates where it is seen that the data tends toward linearity in that plot space although there are significant deviations and the linear log-log fit is not of the quality seen in Figures 217 and 218 for the cartesian curvilinear fit. Figures 221 and 222 present the Optimum Water Content Factors calculated from the data reported by the previously referenced investigators. Tables 62 and 63 contain the related calculated values. These two figures confirm the smooth trend in the factor with gravel content. Figure 223 presents these factors plotted in log-log coordinates. In general, the linear log-log fittings to the data of the other investigators is better than that seen for the WES data in Figures 219 and 220. It is also of interest that the slopes of the best-fit relationships are very similar with the exception of the Garga and Madureira data. Garga and Madureira did not directly determine the water contents of compacted specimens of total material by oven drying because of the lack of large capacity equipment. Instead, they calculated those water contents using Equation (2a) with the water content of the fraction and an assumed value of water content of the gravel. The authors suspect that this practice may explain the difference in slope of their data seen in Figure 223. Also, it is not readily apparent in Figure 223, but it is important to note from the data of Donaghe and Townsend that the Optimum Water Content Factor corresponding to their total material containing 60 percent gravel shows a reversal of trend compared to lower gravel contents. It may be true that just as for the Density Interference Coefficient, the Optimum Water Content Factor coefficient will deviate from linearity in log-log coordinates at some higher gravel content.

Predicting the optimum water
content of the total material

using Optimum Water Content Factors

140. Given the optimum water content of either the minus No. 4 or minus 3/4-in. fraction, the gravel content in the total material, and the corresponding value of the Optimum Water Content Factor, F_{opt}, it is a simple matter to predict the optimum water content of the total material using Equation (12). It is, of course, presupposed that the curve relating Optimum Water Content Factor and gravel content in the total material has been developed and is used to pick off the appropriate value for the factor. Figures 224 and 225 provide the results of predictions of optimum water content of the total materials using Optimum Water Content Factors based on the minus No. 4 and minus 3/4-in. fractions, respectively. Results for data both corrected and uncorrected for equipment size effects are given in these figures. The Optimum Water Content Factors were picked off curves fit by eye to the F_{opt} versus gravel content in the total material data. It was found that plotting of the data to a scale permitting estimation of F_{opt} to the second decimal place was sufficient. In like manner to the predictions for data obtained in this investigation, Figure 226 presents predictions of optimum water content for the various referenced previous investigators' materials employing estimated-fit F_{opt} curves to the data of Figures 221 and 222. It is to be noted that smooth curves could be fit precisely through each data point derived from the USBR and Donaghe and Townsend of Figure 221. This resulted in precise predictions of optimum water contents of their total materials.

141. Figure 227 is intended to indicate the sensitivity of the predicted value of optimum water content to variation in the Optimum Water Content Factor, F_{opt}. To accomplish this, a fixed value of 13 percent was used for the optimum water content of the fraction. This value is approximately the average value for the minus No.4 fractions containing clay fines tested in this investigation. As was the case for the Density Interference Coefficient, I_c, (see Figure 207), Figure 227 shows that the sensitivity of the predicted value of optimum water content with change in Optimum Water Content Factor, F_{opt}, increases with increasing gravel content in the total material.

Developing Optimum Water
Content Factors without large-scale
compaction tests on the total material

142. If one accepts the adequacy of the linearity of the Optimum Water Content Factor versus gravel content of the total material curve in log-log coordinates, a similar procedure to that described previously for obtaining the Density Interference Coefficient curve without large-scale testing of the total material can be employed. Again it is necessary that the minus 3/4-in. fractions of the total materials span a sufficient range in their own gravel contents. The reader is referred back to paragraph 111 for the fundamentals of the procedure which are the same for the Optimum Water Content Factor. The data presented herein indicates that assumption of linearity of the F_{opt} versus gravel content curve in log-log coordinates should probably not be taken above a gravel content in the total material of about 50 percent as was the case for the Density Interference Coefficient, I_c. As was previously pointed out for the Density Interference Coefficient in paragraph 137, the Optimum Water Content Factor also compensates for mold size effects for the same reasons.

Summary comments

143. The authors have presented new methods for predicting the maximum dry unit weight and optimum water content of a total material from tests performed on a fraction for materials containing maximum particle size up to 4-in. (Gordon, Hammond and Miller (1964) tested this maximum size). Those predictions are based on two new parameters termed the Density Interference Coefficient and the Optimum Water Content Factor as previously defined. Their relative numerical values are shown in Figures 228 and 229 for the materials tested in this investigation. The authors are convinced that the data obtained from this investigation and that from other cited investigators support the feasibility of the new methods as long as they are applied to adequately defined families of compaction curves. This is only the same requirement applicable to other methods in use. Since the techniques have been judged on the basis of compaction curves which were established in a conventional manner with absolutely no gerrymandering thereafter, it is reasonable to believe that the results reported can be achieved by USACE division and field laboratories. The values of maximum dry unit weight and optimum water content are subjective judgments, i.e., a compaction curve must be fitted by individual judgment to data points usually exhibiting some scatter.

and several versions of large-scale compaction equipment/procedures have been employed. Consequently, the authors suspect that the fitted curves of Density Interference Coefficient, I_c , and Optimum Water Content Factor, F_{opt} , versus gravel content in the total material may yield estimates of maximum dry unit weight and optimum water content of a total material as good as any other approach. The proof of the pudding will lie in the application of the methods in actual project situations including the treatment of materials with maximum particle size in excess of 4-in.

PART VIII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Laboratory compaction of soils containing large particles

144. The following conclusions are drawn relative to the development of laboratory standard effort compaction test procedures for soils containing large particles:

- a. The standard effort compaction tests developed as an objective of this investigation for a mechanical compactor with 6-in., 12-in. and 18-in. diam molds and a variety of hammer weights was shown to satisfactorily reproduce the optimum water contents and maximum dry unit weights of minus 3/4-in. fractions as obtained in the 6-in. diameter mold (see Figures 100 through 103). By satisfactory replication it is meant that the results fell within current ASTM precison standards of 1.9 percent of the average value of maximum dry unit weight and 10 percent of the mean value of optimum water content. While equipment size and/or procedural effects are not completely absent, the test procedure is concluded to be acceptable for gravelly soils containing a maximum particle size up to 3-in. The test procedure is given in Appendix A.
- b. The standard effort compaction test referred to in a. above satisfactorily reproduced in the 6-in. diameter mold the optimum water contents and maximum dry unit weights of minus No. 4 sieve materials obtained in the 4-in. mold with the hand-held rammer (see Figure 117).
- c. The standard effort compaction test referred to in a. above will not satisfactorily reproduce, according to current ASTM precision standards, the optimum water content or maximum dry unit weight of minus No. 4 materials in the 12-in. or 18-in. diam molds as compared to those values obtained in the 4-in. or 6-in. diam molds (see Figures 110-115 and Tables 28 and 29).
- d. The precision associated with the standard effort compaction test procedure referred to in a. above is not known.

Acceptable degree of scalping to determine compaction parameters of a gravelly soil directly from a fraction

145. EM 1110-2-1906 currently permits scalping of plus No. 4 material as long as that total fraction constitutes less than 5 percent by weight of the total gradation. Compaction tests are then performed on the scalped fraction in the 4-in. diameter mold and the maximum dry unit weight and optimum water content obtained are assumed to be equivalent to those of the total

material. Similarly, scalping of up to 5 percent by weight of plus 3/4-in. material is permitted for compaction tests in the 6-in. diam mold and up to 10 percent by weight of plus 2-in. material is permitted for tests in the 12-in. diam mold. This investigation indicates that there are no general scalping pr ces such as those described above which can be routinely trusted to yield acceptably accurate values of maximum dry unit weight and/or optimum water content of a total material (see PART VI, paragraphs 72-78). In the case of some gradations, the currently prescribed practice would provide an acceptable value of maximum dry unit weight but not of optimum water content and vice versa. A loose interpretation of the general trends seen for the data obtained herein suggests that 5 percent scalping may be excessive for any material containing less than 15 to 20 percent gravel for determination of both maximum dry unit weight and optimum water content.

Prediction of maximum dry unit weight of the total material using the maximum dry unit weight of a fraction with Equation (3)

146. For the materials tested in this investigation, the following conclusions are drawn relative to the usefulness of the modified approximate Ziegler's equation, i.e., Equation (3) for predicting the maximum dry unit weight of a total material using the maximum dry unit weight of a finer fraction. Adequacy of predicted values are based on an approximate single-operator precision of one percent of mean value. Precision of actual values (total material test results) generally thwarted gradation-by-gradation explanation of trends in predicted values. The conclusions apply to materials with either silt or clay fines unless otherwise stated.

a. When the data are corrected for equipment size effects, i.e., when the maximum dry unit weight of the finer fraction is obtained in the same mold as for the total material, there are no significant differences in accuracy of predicted values of maximum dry unit weight of the total material attributable to plasticity of fines (see Part VI, paragraph 96-98). This is true whether the finer fraction was taken as the minus No. 4 or the minus 3/4-in. fraction.

b. When the data are corrected for equipment size effects, the predicted values of maximum dry unit weight of the total material based on that of the minus No. 4 fraction may be acceptably accurate up to gravel contents in the total material between of 45 percent depending on gradation. However, unacceptably inaccurate predictions occurred for materials containing as little as 20 percent gravel. The average results for all gradations indicate a maximum gravel content in the total material of about 35 percent may be usually acceptable for use with Equation (3) [see PART VI, paragraphs 96-98].

c. When the data are corrected for equipment size effects, the predicted values of maximum dry unit weight of the total material based on that of the minus 3/4-in. fraction are acceptably accurate up to gravel content in the total material of 45 to 55 percent depending on the gradation (see Part VI, paragraphs 96-98).

d. When the data are not corrected for equipment size effects as has been conventional practice, plasticity of fines results in significant effects on the accuracy of predicted values of maximum dry unit weight of the total material based on that of the minus No. 4 fraction (see Part VI, paragraph 101).

e. When the data are not corrected for equipment size effects, predictions of the maximum dry unit weight of the total material from that of the minus No. 4 fraction are unacceptably inaccurate at both ends of the gravel content spectrum regardless of the plasticity of fines (see Part VI, paragraph 101).

f. When the data are not corrected for equipment size effects, the finer fraction is taken as the minus No. 4 material and the minus No. 200 material is silt (ML), Equation (3) significantly under-predicts the maximum dry unit weight of the total material at a gravel content as low as about 35 percent depending on gradation. Predictions may be satisfactory up to gravel content of 50 percent for some gradations. Equation (3) significantly over-predicts the maximum dry unit weight of the total material for some gradations containing anywhere from 10 to 40 percent gravel. See Part VI, paragraph 101, for this discussion and reference to appropriate figures.

g. When the data are not corrected for equipment size effects, the finer fraction is taken as the minus No. 4 material and the minus No. 200 material is clay (CH), Equation (3) significantly under-predicts the maximum dry unit weight of the total material at a gravel content as low as about 25 percent depending on gradation. Predictions may be satisfactory up to gravel content of about 55 percent for some gradations. Equation (3) significantly over-predicts the maximum dry unit weight of the total material for some gradations containing anywhere from 10 to 40 percent gravel. See Part VI, paragraph 101.

h. When the data are not corrected for equipment size effects, the finer fraction is taken as the minus 3/4-in. material and the minus No. 200 material is silt (ML), Equation (3) satisfactorily predicts the maximum dry unit weight of the total material containing up to between 40 and 60 percent gravel depending on the gradation (see Part VI, paragraph 101).

i. When the data are not corrected for equipment size effects, the finer fraction is taken as the minus 3/4-in. material and the minus No. 200 material is clay (CH), Equation (3) satisfactorily predicts the maximum dry unit weight of the total material up to 50 or 60 percent gravel in those parent total gradation depending on the gradation. However, Equation (3) also significantly over-predicts the maximum dry unit weight of some of the total materials with gravel contents ranging from 10 to about 55 percent. See Part VI, paragraph 101.

j. Equipment size effects, if unaccounted for, may negate the use of Equation (3) with maximum dry unit weights of either the minus No. 4 or minus 3/4-in. fraction obtained in the 6-in. diam compaction mold to predict the maximum dry unit weight of the total material. See Part VI, paragraph 101.

Prediction of optimum water content of the total material using optimum water content of a fraction with Equation (4)

147. For the materials tested in this investigation, the following conclusions are drawn relative to the usefulness of Equation (4) for predicting optimum water content of a total material from optimum water content of a finer fraction and the water content of the coarser gravel fraction. Adequacy of predicted values is based on an approximate single-operator precision of five percent of mean value and only applies to the range of gravel contents tested of 10 to 64 percent. Precision of actual values (total material test results) generally thwarted a gradation-by-gradation explanation of trends in predicted values. Reference to data corrected for equipment size effects means that the finer fraction was compacted in the same size mold as the total material using the same procedures. Reference to data not corrected for equipment size effects means that the finer fraction was compacted in the 6-in. diam mold while the total material was compacted in either the 12- or 18-in. diam mold. The reader is referred to PART VI, paragraphs 100 and 102 for discussion and figures supporting the following conclusions.

a. The water content of the coarser gravel fraction of only 0.6 percent used in Equation (4) for prediction purposes herein in itself represents a significant contribution to the predicted value of optimum water content of the total material across the range of coarse fraction contents when compared to five percent precision limits. Therefore, the assumption of the absorption (saturated-surface-dry water content) as the water content of the gravel as suggested in EM 1110-1906, Appendix B, may be a poor practice. Some effort should be expended in determining the appropriate value.

b. Whether the data is or is not corrected for equipment size effects and whether the finer fraction is taken as the minus No. 4 or minus 3/4-in., there exists a rough correspondence in trends between predictions of maximum dry unit weight of the total material using Equation (3) and optimum water content using Equation (4). At lower gravel contents for which Equation (3) tends to under-predict the maximum dry unit weight, Equation (4) tends to yield predicted optimum water contents which are wet of the actual value. Conversely, at higher gravel contents for which Equation (3) tends to over-predict maximum dry unit weight, Equation (4) tends to predict optimum water contents which are dry of the actual value.

c. When the data are corrected for equipment size effects and the minus No. 4 fraction is taken as the finer fraction, no difference between predicted value and actual value exceeds +/- one percentage point up to a gravel content of about 50 percent whether the minus No. 200 material is silt or clay. When the finer fraction is taken as the minus 3/4-in. material, no difference exceeds one percentage point up to the maximum gravel content tested of 64 percent. However, one percentage point is approximately three times the precision range of five percent of the mean value.

d. When the data are corrected for equipment size effects and the minus No. 4 fraction is taken as the finer fraction, the trend in predicted values of optimum water content of the total material containing clay fines under-predicts the actual value at lower gravel contents and over-predicts at higher gravel contents. Predicted values for some gradations containing from 10 to about 40 percent gravel were too high (wet) and predicted values for some gradations containing more than 30 percent gravel were too low (dry). Predicted values fell within +/- five percent precision for some gradations containing between 15 and 60 percent gravel.

e. When the data are corrected for equipment size effects and the minus No. 4 fraction is taken as the finer fraction, Equation (4) generally under-predicted values of optimum water content of the total material containing silt fines. The majority of all predicted values fall below the minus five percent precision limit. The estimated band width of the data scatter indicates that some gradations with gravel contents between 10 and 50 percent fall within the five percent precision limits.

f. When the data are corrected for equipment size effects and the minus 3/4-in. fraction is taken as the finer fraction, plasticity of the minus No. 200 material has little influence on the trend of predicted values of optimum water content of the total material. As is the case for predictions based on the minus No. 4 fraction, the data trends from over-prediction at lower gravel content in the parent total gradation to under-prediction at higher gravel content in the parent total gradation. The majority of the predicted values fall outside the +/- five percent precision limits. The band widths inferred from the discrete data indicate that predicted values for some gradations containing 10 to about 50 percent gravel are too high while predicted values for some gradations containing about 45 to 64 percent gravel are too low. Other gradations containing anywhere from 10 percent to 64 percent may result in predicted values within the specified precision range.

g. When the data are not corrected for equipment size effects, the minus No. 4 fraction is taken as the finer fraction and the minus No. 200 material is clay, predicted values of optimum water content of the total material trend from significant over-prediction at lower gravel content to significant under-prediction at higher gravel content. Over-prediction of actual values is as much as two percentage points at the lowest gravel content tested and under-prediction approaches 1.5 percentage points at the highest gravel content tested. Based on the estimated band width encompassing all data, predicted optimum water content may fall above the plus five percent precision limit for some gradations with gravel contents of about 20 to about 50 percent. Predicted values may fall within the +/- five percent limits for some gradations with gravel contents anywhere from about 20 percent to 64 percent. Predicted values may fall below minus five percent precision for some gradations containing 35 to 64 percent gravel.

h. When the data are not corrected for equipment size effects, the minus No. 4 fraction is taken as the finer fraction and the minus No. 200 material is silt, the trend in predicted values of optimum water content of the total material is from slightly higher than actual values to about one percentage point lower than actual values over the range of gravel content. Predictions fall below the minus five percent precision limit for some gradations having gravel contents throughout the tested range of 10 to 64 percent. Predictions fall within the +/- five percent precision range for other gradations also containing from 10 to about 55 percent gravel. No predicted values fall above the plus 5 percent precision limit.

i. When data are not corrected for equipment size effects and the minus 3/4-in. fraction is taken as the finer fraction, plasticity of fines does not significantly effect the trends in predicted values of optimum water content. The predicted values range from as much as about one percentage point above the actual value at the lower end of the gravel content spectrum to about one percentage below the actual value at the upper end. Predicted values for some total gradations containing from 20 to about 60 percent gravel are above the plus five percent prediction limit, those for some gradations containing 20 to 64 percent gravel fall within the +/- five percent precision limits and those for some gradations containing about 45 to 64 percent gravel are below the minus five percent precision limit.

j. The trends in deviations of predicted values of optimum water content from actual values are sufficiently small and consistent for both corrected and uncorrected data that average corrections to predicted values based on gravel content can probably be developed for the range of materials obtained from a given borrow source. This would probably not guarantee conformance to five percent precision limits but would likely meet a 10 percent single-operator precision standard.

Prediction of maximum dry unit weight of the total material from that of a fraction using Equation (5)

148. The following conclusions are drawn relative to the use of Fraction Density Factors in USBR and AASHTO Equation (5) and the NAVFAC Equation (6) tc predict the maximum dry unit weight of the total material. Part VI, paragraphs 103-108 provide discussion and reference figures in support of the following conclusions.

<u>a</u>. The curve(s) relating Fraction Density Factor, r, to gravel content in the total material must be established for each material. Use of single curves or narrow ranges in curves recommended by the USBR and AASHTO as general relationships applicable to all gravelly materials may result in very large errors in predicted values of maximum dry unit weight of the total material obtained from Equation (3). The magnitude of potential error increases with decreasing gravel content.

<u>b</u>. The NAVFAC Equation (6) is equivalent to a single Factor Density Factor versus gravel content curve. Conclusion <u>a</u>. above also applies to this method.

Trends in dry unit weight and water content of a finer fraction when the total material is at maximum dry unit weight

149. As the gravel content of a total material is changed and that material is compacted to its standard effort maximum dry unit weight and optimum water content, the corresponding dry unit weight and water content of a finer fraction also change. The following conclusions relate to those changes in water content and dry unit weight of the minus No. 4 and minus 3/4-in. fractions as determined from tests performed on the total material and the fraction in the same size mold (unless otherwise stated). PART VII, paragraphs 119-123, provide discussion and reference figures in support of the following conclusions.

<u>a</u>. The presence of gravel alters the efficiency of the applied compactive effort in the densification of the minus No. 4 fraction. At lower gravel contents the fraction may be brought to an average dry unit weight which exceeds its standard effort value for its water content. As gravel content increases, the average dry unit weight of the fraction decreases until it becomes less than its standard effort value for its water content. Both of these effects have been termed "gravel interference" herein. Furthermore, over the range in

lower gravel content for which the fraction is densified in excess of its standard effort value, the interference is termed "positive". Conversely, over the range in higher gravel content for which the fraction does not reach its standard effort dry unit weight for its water content, the interference is termed "negative". The gravel content at which the interference transitions from "positive" to "negative" is a function of gradation and plasticity of fines.

b. Conclusion a. above also applies to the addition of oversize gravel to the minus 3/4-in. fraction. In this case the percent oversize at which the interference transitions from "positive" to "negative" is also a function of gradation and plasticity of fines.

c. When the total material is at its maximum dry unit weight, the percent compaction of the minus No.4 or minus 3/4-in. fraction, i.e., the ratio of its average dry unit weight to its own maximum dry unit weight, trends from slightly in excess of 100 percent at lower gravel contents to less than 100 percent at higher gravel contents. For the materials tested in this investigation, plasticity of fines did not significantly affect the percent compaction of the fractions. When the maximum dry unit weight of the fraction is that obtained in the 6-in. diam mold, the trends in percent compaction are not significantly affected.

d. When the total material is at its optimum water content, the water content of the minus No. 4 fraction transitions from the dry side of its optimum water content at low gravel content to the wet side at higher gravel content. The crossover point from dry side to wet side is a function of gradation and plasticity of fines.

e. Conclusion d. above also applies to the water content of the minus 3/4-in. fraction when additional gravel (oversize) is added.

Prediction of the maximum dry unit weight of the total material using Density Interference Coefficients

150. The following conclusions apply to the concept of the Density Interference Coefficient and to its usefulness in predicting the maximum dry unit weight of a total material employing the percent compaction of either the minus No. 4 or minus 3/4-in. fraction. Part VII, paragraphs 128-138 provide discussion and reference figures in support of the following conclusions.

a. Given the maximum dry unit weight of a total material, γ_{tmax}, Equation (1) can be used to determine the corresponding dry unit weight, γ_f, of either the minus No.4 or minus 3/4-in. fraction. The dry unit weight of the fraction, γ_f, the maximum dry unit weight of the fraction, γ_{fmax}, the decimal equivalent of percent gravel in the total material, P_g, and the bulk specific gravity of the gravel, G_m, can be employed to calculate the Density Interference Coefficient, I_c , as follows:

$$I_c = \frac{\frac{\gamma_f}{\gamma_{fmax}}}{P_g G_m}$$

where

γ_f = dry unit weight of the fraction when the total material is at its maximum dry unit weight, pcf

γ_{fmax} = maximum dry unit weight of the fraction, pcf

P_g = percent gravel in the total material as a decimal

G_m = bulk specific gravity of the gravel

For a family of related gradations of gravelly soils, i.e., gradations which may exhibit variable maximum particle size but are otherwise composed of essentially identical gravel, sand and minus No. 200 sieve components mixed in different proportions, the values of Density Interference Coefficient, I_c , for each of the gradations will define a single curve when plotted versus corresponding gravel contents of the total materials. There is some indication that this is also true if the bulk specific gravity of the gravel fraction is a variable while the sand and minus No. 200 sieve components remain related.

b. If the Density Interference Coefficient is plotted against corresponding gravel content in the total material in log-log coordinates, the relationship is linear up to a gravel content of about 50 percent. In the range of 50 to 70 percent gravel content, the relationship becomes curvilinear in log-log space but is linear in cartesian coordinates at an average slope determined from several materials to be -0.013. The linearity of the curve in log-log space below 50 percent gravel and the apparently consistent slope in cartesian space between 50 and 70 percent gravel permit the establishment of the curve by abbreviated testing programs. If the minus 3/4-in. fractions of the family of total material gradation curves span a sufficient range in gravel content, those fractions can be treated as total gradations in determination of Density Interference Coefficients based on the minus No.4 fractions, i.e., γ_f and γ_{fmax} are for minus No.4 fraction. This would allow establishment of the log-log linear portion of the Density Interference Coefficient versus gravel content curve with compaction tests performed in the 6-in. diam mold. It may be possible to perform the compaction tests on the minus No. 4 fractions in the 4-in. diam mold but that practice has not been proven.

c. Given the percent gravel in the total material, the bulk specific gravity of the gravel, and the maximum dry unit weight of the fraction, γ_{fmax} , the value of Density Interference Coefficient picked off the curve of Density Interference Coefficient versus gravel content in the total material can be used to calculate the dry unit weight, γ_f , of the fraction in the total material when it is at its maximum dry unit weight, γ_{tmax} , using the defining equation (see a. above) for Density Interference Coefficient. The dry unit weight, γ_f , of the fraction thus obtained can then be entered into Equation (1) to calculate the maximum dry unit weight of the total material, γ_{tmax} .

d. The value of the maximum dry unit weight of the total material, γ_{tmax} , obtained by the procedure described in c. above is very sensitive to small differences in value of Density Interference Coefficient after the fashion previously described for the Fraction Density Factor, r. It has been shown that this sensitivity does not negate the procedure stated in c. above when the Density Interference Coefficient versus gravel content curve is fitted to the data by eye. However, Density Interference Coefficient versus gravel content data should be plotted to a scale sc as to permit estimation of values of Density Interference Coefficient picked off the fitted curve to the nearest 0.001.

Prediction of the optimum water content of the total material using Optimum Water Content Factors

151. The following conclusions apply to the concept of the Optimum Water Content Factor and to its usefulness in predicting the optimum water content of a total material from that of either the minus No. 4 or minus 3/4-in. fraction. Part VII, paragraphs 139-142, provide discussion and reference figures in support of the following conclusions.

a. Given the optimum water content of either the minus No. 4 or minus 3/4-in. fraction, W_{optf} , the optimum water content of the total material, W_{optt} , and the decimal equivalent of percent gravel in the total material, P_g , the Optimum Water Content Factor, F_{opt} , can be calculated as:

$$F\text{-}opt = \frac{\frac{W_{optf}}{W_{optt}}}{P_g}$$

For a family of related gradations of gravelly soils, the values of the Optimum Water Content Factor, F_{opt} , for each of the gradations will define a single curve when plotted versus corresponding gravel contents of the total materials.

b. If the Optimum Water Content Factor is plotted against corresponding gravel content in the total material in log-log coordinates, the relationship tends to be linear up to gravel contents which may be as high as 70 percent. However, some materials will apparently not yield linearity above about 50 percent gravel content and this limit should be taken as a presumed maximum unless test data are available proving otherwise. If the minus 3/4-in. fractions of the family of total material gradation curves span a sufficient range in gravel content, those fractions can be treated as total materials in determination of the Optimum Water Content Factors based on the minus No. 4 fractions, i.e., w_{opf} and w_{optt} are for the minus No. 4 fraction. This would allow establishment of the log-log linear portion of the Optimum Water Content Factor versus gravel content curve with compaction tests performed in the 6-in. diam mold. It may be possible to use the 4-in. diam mold for compaction tests on the minus No. 4 fraction but that practice has not been proven.

c. Given the percent gravel in the total material and the optimum water content of the fraction, the Optimum Water Content Factor picked off the curve of optimum water content factor versus gravel content in the total material can be used to calculate the optimum water content of the total material using the defining equation (see a. above) for Optimum Water Content Factor.

d. The value of optimum water content of the total material obtained by the procedure described in c. above is sensitive to small differences in value of Optimum Water Content Factor. It has been shown that this sensitivity does not negate the procedure stated in c. above when the Optimum Water Content Factor versus gravel content in the total material curve is fitted by eye to the data. However, the Optimum Water Content Factor versus gravel content data should be plotted to a scale permitting estimation of the values of the factor picked off the fitted curve to the nearest 0.01.

Recommendations

152. The following recommendations are made:

a. The laboratory compaction test for earth-rock mixtures developed as part of this investigation and stated in Appendix A, should be incorporated into EM 1110-2-1906, "Laboratory Soils Testing" as a replacement for the current hand-held rammer test procedure employing the 12-in. diam mold (Appendix VIA).

b. The scalping with replacement procedure currently allowed in EM 1110-2-1906 should be abandoned.

c. The current scalping allowances of EM 1110-2-1906 should be critically reconsidered in light of the findings of this investigation. The alternative to those allowances is their abandonment, i.e., the forbiddance of any scalping.

d. The use of Density Interference Coefficients in the prediction of maximum dry unit weight of total materials from tests performed on either the minus No. 4 or minus 3/4-in. fraction should be assessed by application in actual project cases. If the technique proves as reliable as has been indicated in this report, EM 1110-2-1911 "Construction Control of Earth and Rockfill Dams," should be revised to cite the method in lieu of the use of Equation (3) as is currently recommended in Appendix B of that Engineer Manual.

e. The use of Optimum Water Content Factors in the prediction of optimum water content of total materials from tests performed on either the minus No.4 or minus 3/4-in. fraction should be assessed by application in actual project cases. If the technique proves as reliable as has been indicated in this report, EM 1110-2-1911, should be revised to cite the method in lieu of the use of Equation (4) as is currently recommended in Appendix B of that Engineer Manual.

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Table 1

ASTM Designations D 698-78 and D 1557-78 Precision Standards

	Standard Deviation	Acceptable Range of Two Results, Expressed as Percent of Mean Value
Single-operator precision:		
Maximum dry unit weight	---	1.9
Optimum water content	---	9.5
Multi-laboratory precision:		
Maximum dry unit weight	± 1.66 pcf	4.0
Optimum water content	± 0.86 percentage points	15.0

Table 2

Results of Umpire Tests on Standard Soil Samples

Type of test	ML SOIL Average*	ML SOIL Range**	CL SOIL Average*	CL SOIL Range**	CH SOIL Average*	CH SOIL Range**
LL, percent	28	27-30	35	32-37	59	54-64
PL, perent	24	22-26	23	22-25	24	22-27
Plasticity Index†	5	3-6	12	9-14	35	31-39
Moisture-Density Standard Effort:						
Optimum Water Content, percent	16.8	15.9-17.3	16.4	15.6-17.5	21.7	21.2-22.5
Maximum Dry Density, pcf	106.0	104.8-107.0	109.5	108.7-110.5	98.6	97.5-100.2
Moisture-Density Modified Effort:						
Optimum Water Content, percent	14.3	14.0-14.8	13.5	12.8-14.2	15.1	14.3-16.0
Maximum Dry Density, pcf	111.8	111.3-112.7	117.7	116.5-118.1	114.0	112.5-115.9
Specific Gravity:	2.72	2.70-2.74	2.70	2.68-2.73	2.70	2.67-2.72
Grain Size, percent finer than:						
.074 mm	97	95-98	99	96-100	97	96-99
.040 mm	84	80-88	89	83-93	90	84-95
.015 mm	40	30-50	51	39-60	75	69-80
.005 mm	15	12-18	26	23-29	55	50-60
.002 mm	12	9-14	21	18-24	44	38-49

* Average of all individual tests
** Represents minimum and maximum values of actual test results.
† Ranges are computed from the test values for liquid and plastic limit.

Table 3

Statistical Analysis of ML Soil Considering All Commercial Laboratory Results

TYPE OF TEST	NO. OF LABORATORIES CONDUCTING TESTS	AVERAGE VALUE DETERMINED	STANDARD DEVIATION
LL	96	27.0 percent	1.7
PL	85	23.6 percent	2.4
PI	80	3.8	2.1
Standard density test:			
Moisture content	98	16.3 percent	1.3
Density	98	105.9 pcf	1.9
Modified density test:			
Moisture content	97	13.8 percent	0.92
Density	97	112.5 pcf	2.09
Specific gravity	65	2.69	0.054
Grain Size, percent finer than:			
0.076 mm	71	94.9 percent	6.9
0.040 mm	67	79.4 percent	12.5
0.015 mm	66	30.2 percent	6.7
0.005 mm	68	11.3 percent	3.5
0.002 mm	62	8.6 percent	3.2

Table 4

Statistical Analysis of CL Soil Considering All Commercial Laboratory Results

TYPE OF TEST	NO. OF LABORATORIES CONDUCTING TESTS	AVERAGE VALUE DETERMINED	STANDARD DEVIATION
LL	99	32.7 percent	2.3
PL	99	22.4 percent	2.8
PI	99	10.4	3.6
Standard density test:			
Moisture content	97	15.9 percent	1.1
Density	97	109.7 pcf	2.4
Modified density test:			
Moisture content	99	13.1 percent	0.82
Density	99	115.8 pcf	14.2
Specific gravity	65	2.66	0.060
Grain Size, percent finer than:			
0.076 mm	71	97.9 percent	2.4
0.040 mm	67	84.0 percent	11.0
0.015 mm	66	43.9 percent	10.6
0.005 mm	68	21.9 percent	6.5
0.002 mm	62	17.9 percent	4.7

Table 5

Statistical Analysis of CH Soil Considering All Commercial Laboratory Results

TYPE OF TEST	NO. OF LABORATORIES CONDUCTING TESTS	AVERAGE VALUE DETERMINED	STANDARD DEVIATION
LL	99	54.3 percent	5.4
PL	99	22.2 percent	3.4
PI	99	32.0 percent	5.[illegible]
Standard density test:			
Moisture content	98	20.6 percent	2.7
Density	98	99.6 pcf	2.5
Modified density test:			
Moisture content	97	15.2 percent	1.9
Density	97	113.3 pcf	2.8
Specific gravity	65	2.63	0.115
Grain Size, percent finer than:			
0.076 mm	71	95.6 percent	6.8
0.040 mm	68	84.2 percent	11.2
0.015 mm	65	68.6 percent	8.8
0.005 mm	67	47.6 percent	9.1
0.002 mm	62	38.5 percent	7.4

Table 6

Precision Limits for ACIL Study Results

SOIL	MEAN VALUE	STANDARD DEVIATION	DIFFERENCE 2σ LIMIT	PERCENT OF MEAN VALUE
		MAXIMUM DRY UNIT WEIGHT		
ML	105.9 pcf	1.9 pcf	5.3 pcf	5.0
CL	109.7 pcf	2.4 pcf	6.6 pcf	6.0
CH	99.6 pcf	2.5 pcf	6.9 pcf	6.9
		OPTIMUM WATER CONTENT		
ML	16.3 percent	1.3*	3.6*	22.1
CL	15.9 percent	1.1*	3.0*	18.9
CH	20.6 percent	2.7*	7.5*	36.4

* Percentage points

Table 7

Precision Limits for CE Division Lab Results on ACIL Standard Soils

SOIL	MEAN VALUE	STANDARD DEVIATION	DIFFERENCE 2σ LIMIT	PERCENT OF MEAN VALUE
		MAXIMUM DRY UNIT WEIGHT		
ML	105.7 pcf	0.8 pcf	2.2 pcf	2.1
CL	109.2 pcf	1.1 pcf	3.0 pcf	2.7
CH	97.9 pcf	1.4 pcf	3.9 pcf	4.0
		OPTIMUM WATER CONTENT		
ML	17.3 percent	0.6*	1.7*	9.8
CL	16.6 percent	0.8*	2.2*	13.2
CH	22.4 percent	1.8*	5.0*	22.3

* Percentage points

Table 8

Estimated Precision Limits for ACIL Umpire Lab Results

SOIL	MEAN VALUE	ESTIMATED* STANDARD DEVIATION	DIFFERENCE 2σ LIMIT	PERCENT OF MEAN VALUE
		MAXIMUM DRY UNIT WEIGHT		
ML	106.0 pcf	0.55 pcf	1.5 pcf	1.4
CL	109.5 pcf	0.45 pcf	1.2 pcf	1.1
CH	98.6 pcf	0.68 pcf	1.9 pcf	1.9
		OPTIMUM WATER CONTENT		
ML	16.8 percent	0.35**	1.0**	6.0
CL	16.4 percent	0.48**	1.3**	7.9
CH	21.7 percent	0.32**	0.9**	4.1

* Standard deviations estimated by taking range of the data to be 4σ
** Percentage points

Table 9

British Road Research Laboratory (RRL) Study

Soil	Mean	Standard Deviation	Difference Two-Sigma Precision Limit	Percent of Mean Value
		MULTI-LABORATORY		
		MAXIMUM DRY UNIT WEIGHT		
Clayey Sand, CL	111.7 pcf	1.8 pcf	5.0 pcf	4.5
Gault Clay, CH	99.8 pcf	2.0 pcf	5.5 pcf	5.5
Weald Clay, CH	103.6 pcf	2.1 pcf	5.8 pcf	5.6
		OPTIMUM WATER CONTENT		
Clayey Sand, CL	15.0 percent	1.0*	2.8*	18.7
Gault Clay, CH	21.0 percent	2.0*	5.5*	26.2
Weald Clay, CH	19.0 percent	3.3*	9.1*	47.9
		MULTI-OPERATOR**		
		MAXIMUM DRY UNIT WEIGHT		
Sandy Clay, CL	112.9 pcf	1.4 pcf	3.9 pcf	3.4
Gault Clay, CH	102.3 pcf	1.3 pcf	3.6 pcf	3.5
Weald Clay, CH	106.1 pcf	1.7 pcf	4.7 pcf	4.4
		OPTIMUM WATER CONTENT		
Sandy Clay, CL	16.0 percent	0.8*	2.2*	13.8
Gault Clay, CH	22.0 percent	1.2*	3.3*	15.0
Weald Clay, CH	20.0 percent	1.4*	3.9*	19.5

(Continued)

Table 9(Concluded)

SINGLE-OPERATOR***

Soil	Mean	Standard Deviation	Difference Two-Sigma Precision Limit	Percent of Mean Value
		MAXIMUM DRY UNIT WEIGHT		
Gault Clay, CH	101.7 pcf	0.8 pcf	2.2 pcf	2.2
		OPTIMUM WATER CONTENT		
Gault Clay, CH	22.0 percent	0.2*	0.6*	2.7

* Percentage points
** Multi-operator case are results obtained by 8 operators within RRL
*** Single-operator case represents 8 tests by one operator within RRL

Table 10

Summary of test data; Gordon, Hammond and Miller, 1964

Laboratory Sample No	Material Grading Group	Date Tested	Maximum Particle Size, in.	Plus No 4, %	Minus No 4, Specific Gravity	Atterberg Limits: Plasticity Index, %	Atterberg Limits: Liquid Limit, %	Maximum Density, lb ft³	Optimum Moisture Content, %
1-4043	*D*	10-20-61	No. 4	0	2.84	18	35	126.6	12.2
		10-30-61	3/4	35				135.9	9.1
		10-30-61	1 1/2	50				139.8	7.7
		10-17-61	4	62				144.3	7.7
1-4044	*B*	10-21-61	No. 4	0	2.85	18	36	124.3	13.0
		10-21-61	3/4	24				130.1	11.3
		10-21-61	1 1/2	34				133.4	9.9
		10-17-61	4	43				133.8	9.5
1-4045	*A*	10-21-61	No. 4	0	2.83	10	27	122.0	13.3
		10-21-61	3/4	18				128.1	11.7
		10-21-61	1 1/2	26				131.0	10.6
		10-18-61	4	35				131.6	8.3
1-4046	*B*	10-20-61	No. 4	0	2.85	12	30	123.0	13.2
		10-30-61	3/4	21				192.9	11.1
		10-30-61	1 1/2	32				134.4	9.6
		10-18-61	4	42				132.3	9.8
1-4047	*C*	10-20-61	No. 4	0	2.84	12	35	118.7	15.0
		10-27-61	3/4	25				128.1	12.0
		10-24-61	1 1/2	38				133.0	10.1
		10-26-61	4	50				134.3	9.6
1-4047A	*C*	11-2-61	No. 4	0	2.83	14	34	119.4	14.6
		11-8-61	3/4	25				128.7	11.3
		11-8-61	1 1/2	38				133.6	9.8
		11-3-61	4	50				132.8	9.9
1-4048	*D*	10-20-61	No. 4	0	2.85	15	32	128.0	11.5
		10-27-61	3/4	30				135.0	9.0
		10-27-61	1 1/2	44				139.8	7.9
		10-18-61	4	58				141.1	8.0
1-4687[a]		11-14-61	No. 4	0	2.84	16	33	126.0	12.2
		3-3-62	3	40				136.6	9.8
		3-3-62	3	50				140.1	7.5
		3-3-62	3	60				142.6	7.0
		3-9-62	3	50				144.6	6.8[b]
2-890[a]		4-5-62	No. 4	0	2.80	10	32	118.8	14.9
		4-6-62	3	40				135.2	9.1
		4-7-62	3	50				138.4	8.5
		4-6-62	3	60				140.4	7.7
		4-27-62	3	50				143.0	7.0[b]

[a] These were synthetic composites prepared by adding to the soil fraction various percentages of rock to represent the grading group desired.

[b] For compactive effort of 56,250 ft-lb ft³.

Table 11

Specific Gravity and Absorption Values for the Indicated Rock Fraction (After Gordon, Hammond and Miller, 1964)

NOTE.—Averages and standard deviation are based on twelve tests.

Material Size	Average Specific Gravity				Standard Deviation	
	Oven Dry*	Saturated Surface Dry	Apparent	Absorption, %	Oven Dry	Absorption, %
Plus No. 4 to minus 3/8 in.	2.67	2.76	2.92	3.2	0.07	0.6
Plus 3/8 in. to minus 3/4 in.	2.72	2.79	2.91	2.4	0.04	0.4
Plus 3/4 in. to minus 1½ in.	2.78	2.82	2.91	1.6	0.05	0.4
Plus 1½ in. to minus 3 in.	2.83	2.85	2.90	0.8	0.06	0.4
Plus 3 in. to minus 4 in.	2.85	2.87	2.92	0.8	0.10	0.4

* Bulk Specific Gravity

Table 12

Compaction Testing Equipment

(After Gordon, Hammond and Miller, 1964)

MATERIAL SIZE							
Maximum size, standard procedure	No. 4	3/4 in.	1 1/2 in.		3 in.		
Maximum size, special procedures used in testing program		No. 4	No. 4, 3/4 in.		No. 4, 3/4 in., 1 1/2 in.		4 in.
MOLD							
Volume, ft^3	0.05	0.075	0.20		0.667		2.00
Height, in.	6.075	4.567	6.890		10.354		15.20
Diameter, in.	4.244	5.984	8.039		11.878		17.02
HAMMER							
			A[a]	*B*[a]	*A*[a]	*B*[a]	
Weight, lb	10	10	10	30	33.5	127.5	33.5
Free drop, in.	18	18	18	18	18	18	18
Face diameter, in.	2.00	2.00	2.00	3.94	2.94	5.94	2.94
Face area, in^2	3.14	3.14	3.14	12.192	6.777	18.378	6.777
LAYERS							
Number, total	5	3	3	3	3	3	3
Surface, in^2	13.361	28.126	50.507	50.507	110.791	110.791	227.515
Compacted thickness, in.	1.215	1.522	2.297	2.297	3.451	3.451	5.067
EFFORT							
Tamper blows per layer	13	33	89	30	88	23	265
Ft lb/ft^3	20 000	20 000	20 000	20 000	20 000	20 000[b]	20 000

[a] Column *A* lists the hammers first used with that particular mold size. As a result of the study however, new hammers were developed and are now used with specific mold sizes—these are listed under column *B*.

[b] Two additional tests were run with the 127.5-lb hammer. For both tests 56,250 ft lb/ft^3 of compactive effort were used.

Table 13

Compaction Tests Using Hand-Held Sliding Weight Rammer and Howard Mechanical Compactor (After Donaghe and Townsend, 1973)

Mold Diam in.	Compactive Effort ft-lb/ft^3	Rammer* Wt lb	Rammer* Diam of Circular Face in.	Drop in.	No. of Layers	Blows per Layer	Complete Coverages of Mold Area	Blows per Coverage: Along Circumference of Mold	Blows per Coverage: At Center of Specimen
				Vicksburg Silty Clay (CL)					
4	12,300	5.5	2	12	3	25	-	-	-
6	12,420	5.5	2	12	3	56	2	24	4
12	12,262	24.7	6	24	3	65	4	16**	-
18	12,299	24.7	6	24	3	220	7	24†	6††
				DeGray Dam Clayey Sandy Gravel (GC)					
4	12,300	5.5	2	12	3	25	-	-	-
6	12,420	5.5	2	12	3	56	2	24	4
12	12,262	24.7	6	24	3	65	4	16**	-
18	12,299	24.7	6	24	3	220	7	24†	6††

* Compaction equipment used:
hand compaction: 4-in. mold
hand and mechanical compaction: 6-in. mold
mechanical compaction: 12- and 18-in. molds

** Plus 1 on last coverage

† Plus 6 on last coverage

†† Plus 4 on last coverage

Table 14

Compaction Tests Using Hand-Held Sliding Weight Rammer and Howard Mechanical Compactor (After Donaghe and Townsend, 1975)

Mold Diam in.	Compaction Effort ft-lb/ft^3	Rammer* Weight lb	Rammer* Diam of Circular Face in.	Rammer* Drop in.	No. of Layers	Blows per Layer	Complete Coverage of Mold Area	Blows per Coverage: Along Circumference of Mold	Blows per Coverage: At Center of Specimen
6	12,420	5.5	2	12	3	56	2	24	4
18	12,299	24.7	6	24	3	220	7	24**	6†

* Compaction equipment: hand-held and mechanical compaction, 6-in.-diam mold; mechanical compaction, 18-in.-diam mold.

** Plus 6 on last coverage.

† Plus [illegible] on last coverage.

Table 15

Summary of Compaction Data (After Donaghe and Townsend, 1975)

Effect Investigated	Type of Compactor Used	Mold Diam in.	Maximum Particle Size	Gravel Content %	Fines Content %	Maximum Dry Unit Weight γ_d lb/ft^3	Optimum Water Content w, %
Equipment size	Mechanical	6	No. 4 sieve	0	25	130.9	8.6
		18				133.9	6.9
		6	3/4*	40	25	131.1	7.9
		18				134.1	7.3
Removal and replacement of coarse particles	Mechanical	18	3/4*	40	25	134.1	7.3
			3**			138.0	5.9
Gravel content (large-scale tests)	Mechanical	18	No. 4 sieve	0	25	133.9	6.9
			3**	10		135.0	6.7
				20		136.1	6.1
				30		137.2	5.7
				40		138.0	5.9
				50		137.1	5.8
				60		134.9	5.2
				100		112.0	+
Gravel content (small-scale tests)	Mechanical	6	No. 4 sieve	0	25	130.9	8.6
			3/4*	10		133.5	7.7
				20		132.5	8.1
				30		132.3	8.1
				40		131.1	7.9
				50		131.9	7.8
				60		129.5	9.5
				100		103.6	+
Gravel content (small-scale tests)	Hand-held	6	No. 4 sieve	0	25	132.6	8.0
			3/4*	10		132.5	7.0
				20		131.8	7.9
				30		132.0	7.9
				40		132.0	7.9
				50		129.3	8.0
				60		128.5	9.2
				100		101.2	+
Fines content (large-scale tests)	Mechanical	18	3**	40	15	141.8	4.9
					25	138.0	5.9
					35	133.3	7.5
Fines content (small-scale tests)	Mechanical	6	3/4*	40	15	134.8	7.4
					25	131.1	7.9
					35	126.6	9.4

* Scalped and replaced material.
** Full-scale material.
\+ Single-point test performed on dry material.

Table 16

Characteristics of Compaction Equipment (After Garga and Madureira, 1985)

Nominal mould diameter, in. (cm) (1)	Mould		Rammer			Ram diameter / Mould diameter (7)
	Height, in. (cm) (2)	Volume, cu ft (cm^3) (3)	Weight, lb (kg) (4)	Drop, in. (cm) (5)	Base diameter, in. (cm) (6)	
4 (10)	4.6 (11.7)	0.033 (945)	5.5 (2.5)	12 (30)	2 (5.01)	0.5
6 (15)	4.6 (11.7)	0.074 (2,120)	10 (4.5)	18 (45)	2 (5.01)	0.3
12 (30)	15.1 (38.4)	1.00 (28,340)	81.8 (37.2)	45.6 (18)	5.8 (14.7)	0.5
20 (50)	14.9 (38.0)	2.74 (77,700)	111 (50.5)	46.3 (19.2)	9.4 (24.0)	0.5

Table 17

Compaction Test Characteristics (After Garga and Madureira, 1985)

Compactive effort (1)	NUMBER OF LAYERS × NUMBER OF RAMMER DROPS PER LAYER — Mould Diameter			
	4 in. (10 cm) (2)	6 in. (15 cm) (3)	12 in. (30 cm) (4)	20 in. (50 cm) (5)
Standard (12,375 ft-lb/cu ft)	3 × 25[a]	3 × 55[a]	3 × 33	3 × 66
Intermediate (24,985 ft-lb/cu ft)	4 × 40[a]	4 × 32[a]	4 × 51	4 × 102
Modified (56,250 ft-lb/cu ft)	5 × 25[b]	5 × 55[b]	5 × 91	—

[a]2.5 kg rammer.
[b]4.5 kg rammer.

Table 18

Results of Compaction Tests (After Garga and Madureira, 1985)

Series (1)	Compaction energy (2)	Mould diameter, ϕ, in. (cm) (3)	Maximum size, ϕ_{max} (4)	Gravel content (%) (5)	Total Material: γ_d max (g/cm^3) (6)	Total Material: w/c opt (%) (7)	Minus No. 4 Sieve Fraction: γ_d (g/cm^3) (8)	Minus No. 4 Sieve Fraction: w/c (%) (9)	Plus No. 4 Sieve Fraction: Water absorption condition (10)	Plus No. 4 Sieve Fraction: G_b (11)	Physical characteristics of minus No. 4 sieve fraction, LL-PI-G_s-%-200-%<2$_\mu$ (12)	Testing variable (13)
1	Standard	4	No. 4	0	1.92	12.3	—	—	Saturated and	2.59	26-6-2.79-41-13	Gravel content
		6	3/4 in.	30	2.04	10.2	1.86	14.0	surface dried			
				40	2.07	9.5	1.83	14.8				
				50	2.09	8.3	1.76	15.8				
				60	2.12	7.9	1.67	18.2				
				70	2.11	5.7	—	—				
2	Standard	4	No. 4	0	1.88	14.6	—	—	Saturated and	2.59	28-7-2.81-51-16	Gravel content
		12	1-1/2 in.	30	2.00	10.7	1.82	14.7	surface dried			
		(30)		40	2.05	9.7	1.80	15.4				
				50	2.09	8.4	1.77	16.4				
				60	2.12	7.3	1.67	16.7				
3	Intermediate	4	No. 4	0	1.92	14.1	—	—	Dry	2.59	30-9-2.84-46-23	Gravel content
		4	3/4 in.	30	2.10	9.4	1.94	13.6				
				40	2.11	8.1	1.87	14.0				
				50	2.13	6.3	1.80	12.3				
				60	2.15	5.5	1.72	13.5				
4	Intermediate	4	No. 4	0	2.00	12.6	—	—	Saturated and	2.59	27-7-2.86-45-20	Gravel content
		6	3/4 in.	30	2.09	9.9	2.00	14.2	surface dried			
				40	2.11	9.0	1.88	14.9				
				50	2.15	7.2	1.84	14.3				
				60	2.19	6.1	1.78	15.2				
				65	2.20	6.6	1.68	18.0				
				70	2.19	5.8	1.62	18.8				
5	Intermediate	4	No. 4	0	1.95	14.8	—	—	Dry	2.59	30-9-2.84-46-23	Gravel content
		6	1-1/2 in	30	2.10	9.1	1.93	13.9				
				40	2.15	8.3	1.92	13.5				
				50	2.16	6.6	1.86	13.3				
				60	2.19	5.7	1.76	13.8				

(Continued)

Table 18 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
6	Intermediate	4	No. 4	0	1.96	13.0	—	—	—	—	29-9-2.82-54-20	Gravel content
		12	1-1/2 in.	30	2.08	9.0	1.91	12.3	Saturated and	2.59		
		(30)		40	2.13	7.7	1.90	12.1	surface dried			
				50	2.13	7.0	1.82	13.0				
				60	2.18	6.1	1.75	14.0				
				70	2.21	5.4	1.65	15.4				
7	Intermediate	4	No. 4	0	1.97	13.5	—	—	—	—	30-8-2.76-45-18	Gravel content
		12	3 in.	30	2.02	10.3	1.84	13.9	Saturated and	2.59		
		(30)		40	2.09	8.4	1.86	13.4	surface dried			
				50	2.15	6.8	1.83	13.0				
				60	2.18	6.0	1.74	13.8				
				70	2.21	5.6	1.65	16.0				
8	Intermediate	4	No. 4	0	1.97	12.7	—	—	—	—	28-8-2.87-45-20	Gravel content
		20	3 in.	30	2.08	10.2	1.92	13.9	Saturated and	2.59		
		(50)		40	2.11	8.4	1.87	13.4	surface dried			
				50	2.14	7.1	1.84	14.1				
				60	2.20	5.6	1.80	13.3				
				70	2.23	5.0	1.70	14.0				
9	Modified	4	No. 4	0	2.03	12.8	—	—	—	—	30-8-2.81-55-33	Gravel content
		6	3/4 in.	30	2.13	9.4	1.99	12.7	Saturated and	2.59		
				40	2.17	7.9	1.96	12.2	surface			
				70	2.20	5.6	1.63	17.0				
10	Modified	4	No. 4	0	2.10	10.3	—	—	—	—	29-10-40-16	Gravel content
		12	1-1/2 in.	30	2.13	8.8	1.98	11.3	Saturated and	2.56		
		(30)		40	2.14	8.4	1.96	12.4	surface dried			
				50	2.18	7.1	1.95	11.8				
				60	2.18	7.7	1.85	14.4				
				65	2.20	6.6	1.82	13.7				
				70	2.20	6.2	1.74	14.2				
11	Modified	4	No. 4	0	1.99	13.3	—	—	—	—	30-9-2.80-55-27	Gravel content
		12	1-1/2 in.	30	2.08	10.1	1.92	13.9	Saturated and	2.59		
		(30)		50	2.17	7.4	1.87	13.5	surface dried			
				65	2.20	6.2	1.73	15.8				
12	Modified	4	No. 4	0	2.06	10.8	—	—	—	—	—	Gravel content
		12	3 in.	40	2.14	8.8	1.96	12.8	Saturated and	2.59		
		(30)		50	2.16	8.3	1.85	13.0	surface dried			
				60	2.22	7.4	1.89	14.0				
				65	2.24	6.6	1.88	13.6				
				70	2.23	6.2	1.78	14.2				

(Continued)

Table 18 (concluded)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
13	Vibratory	6	3/4 in	100	1.75	—	1.53	0	Dry	2.59	—	
	Method	6	1-1/2 in	100	1.78	—	1.59	—				
	ASTM-D 2049	11	1-1/2 in	100	1.85	—	1.65	—				
		11	3 in	100	1.91	0	1.66	0				
14	Intermediate	(30)	1-1/2 in	50	2.14	7.5	1.84	14.6	Oven dried	2.59		Tests in groups of two to
				50	2.14	7.8	1.82	14.5	Saturated	2.59		verify influence of
				50	2.11	7.6	1.79	15.0	Oven dried	2.56		saturation of coarse
				50	2.10	8.9	1.78	15.0	Saturated	2.56		fraction
		4	No. 4	0	1.95	14.1	—	—	—	—	29-7-2.82-50-16	
15	Intermediate	4	No. 4	0	1.94	14.4	—	—	—	—	30-8-2.82-55-29	Tests in groups of three
		6	3/4 in	40	2.09	9.4	1.84	15.2	Dry	2.59		to verify influence of
		12	1-1/2 in	40	2.09	8.9	1.86	14.5				maximum particle size
		20	3 in	40	2.09	9.1	1.86	14.5				for equal percentage of
		6	3/4 in	50	2.12	8.2	1.80	17.5				gravel content; and the
		12	1-1/2 in	50	2.14	7.4	1.82	14.8				validity of substitution
		20	3 in	50	2.14	7.6	1.82	15.2				method
		6	3/4 in	60	2.15	6.9	1.94	16.5				
		12	1-1/2 in	60	2.16	6.0	1.95	15.0				
		20	3 in	60	2.18	5.0	1.98	14.8	Dry	2.59	31-9-2.80-49-26	Tests in groups of two to
16	Intermediate	6	3/4 in	40	2.10	9.5	1.86	15.8			31-8-2.86-48-25	verify influence of size
		12	3/4 in	40	2.08	8.8	1.85	14.9			30-8-2.80-45-25	of mould used in this
		12	1-1/2 in	50	2.12	7.8	1.78	15.7			52 9-2.82-54-27	investigation (implicitly
		12	1-1/2 in	50	2.12	7.8	1.80	15.6				includes effects of
		6	3/4 in	50	2.12	8.0	1.80	16.0				rammer sizes and layer
		12	3/4 in	50	2.09	7.8	1.75	15.6				heights)
		12	1-1/2 in	60	2.15	6.3	1.71	25.4	Dry	2.59	Lower band	Tests in groups of two to
		20	1-1/2 in	60	2.13	6.5	1.69	15.4			Upper band	verify influence of
17	Intermediate	12	1-1/2 in	50	2.18	7.8	1.89	15.6			Lower band	grain size distribution
				50	2.18	7.4	1.88	15.2				
				60	2.17	5.8	1.76	14.0				
				60	2.16	6.3	1.74	15.8			Upper band	
18	Intermediate	4	3/4 in	30	2.08	10.1	—	—	Dry	2.59	31-9-2.80-49-26	Tests in groups of two to
		6		30	2.10	9.6	—	—				verify effect of mould
		4		40	2.11	8.1	—	—				equipment size
		6		40	2.13	8.6	—	—				
		4		50	2.14	7.2	—	—				
		6		50	2.18	7.0	—	—				
19	Intermediate	6	1-1/2 in	30	2.07	10.0	1.91	15.0	Dry	2.59	29-7-2.82-49-16	Tests in groups of two to
		12		30	2.07	9.8	1.91	13.8				verify effect of
		6		50	2.15	7.9	1.83	15.8				equipment size
		12		50	2.15	7.7	1.82	15.4				
		6		70	2.17	5.8	1.60	19.2				
		12		70	2.19	5.5	1.60	19.4				

Table 19

Test Gradations

Gradation No.	Description
1	MINUS 3-IN. FULL-SCALE MATERIAL, 20 percent plus 3/4-in., 28 percent gravel, 28 percent minus No. 200
1A	MINUS 2-IN. FRACTION, 12 percent plus 3/4-in., 20.9 percent gravel, 30.8 percent minus No. 200
1B	MINUS 3/4-IN. FRACTION, 10 percent gravel, 35 percent minus No. 200
1C	MINUS NO. 4 FRACTION, 38.9 percent minus No. 200
2	MINUS 3-IN. FILL-SCALE MATERIAL, 40 percent plus 3/4-in., 46 percent gravel, 21 percent minus No. 200
2A	MINUS 2-IN. FRACTION, 23.6 percent plus 3/4-in., 31.2 percent gravel, 26.8 percent minus No. 200
1B	MINUS 3/4-IN. FRACTION identical to that of Gradation 1
1C	MINUS NO. 4 FRACTION identical to that of Gradation 1
3	MINUS 3-IN. FULL-SCALE MATERIAL, 20 percent plus 3/4-in., 52 percent gravel, 28 percent minus No. 200
3A	MINUS 2-IN. FRACTION, 18.4 percent plus 3/4-in., 51 percent gravel, 28.6 percent minus No. 200
3B	MINUS 3/4-IN. FRACTION, 40 percent gravel, 35 percent minus No. 200
3C	MINUS NO. 4 FRACTION, 58.3 percent minus No. 200
4	MINUS 3-IN. FULL-SCALE MATERIAL, 40 percent plus 3/4-in., 64 percent gravel, 21 percent minus No. 200
4A	MINUS 2-IN. FRACTION, 35.8 percent plus 3/4-in., 61.5 percent gravel, 22.5 percent minus No. 200
3B	MINUS 3/4-IN. FRACTION identical to that of Gradation 3
3C	MINUS NO. 4 FRACTION identical to that of Gradation 3

Table 20

Summary of Hammers, Compaction Procedures, and Mold Dimensions

HAMMERS AND COMPACTION PROCEDURES

Mold Diam. in.	No. Layers	Hammer Diam. in.	Hammer Weight lbs.	Blows Per Layer	No. Complete Coverages of Specimen Area Per Layer	Peripheral Blows Per Coverage	Central Blows Per Coverage	Total Energy ft-lb/ft^3
HAMMER DROP HEIGHT FOR ALL TESTS WAS 12 INCHES								
6	3	2	5.5	56	3	12	6(1)	12,467
12	3	4	38.8	84	5	12	5(2)	12,390
			58.8	55	3	12	6(1)	12,493
			78.8	41	2	12	8(1)	12,532
		6	131.4	25	2	12	0	12,538
18	3	6	131.4	83	5	12	5(3)	12,243

(1) Plus 2 extra central blows for the last coverage
(2) Minus 1 central blow for last coverage
(3) Minus 2 central blows for last coverage

MOLD DIMENSIONS

Nominal Mold Diameter in.	Precise Mold Diameter in.	Precise Height in.	Precise Volume cu ft
6	5.933	4.573	0.075
12	11.997	12.013	0.786
18	17.989	18.019	2.651

Table 21

Compaction Test Data Summary

Tests On Minus 3/4-in. Fractions to Determine Procedures for Duplicating 6-in. Diameter Mold Test Results Using 12-in. Diameter Mold

GRADATION 1B, SILT (ML) FINES, 10 PERCENT GRAVEL

TEST NO.	SPECIMEN NO.	HAMMER DIAMETER IN.	HAMMER WEIGHT LBS	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
1	1	2	5.5	4.61	128.9
	2			6.40	129.9
	3	(6-IN. MOLD)		6.94	131.4
	4			6.60	131.5
	5			8.40	131.0
	6			10.21	128.9
2	1	4	38.4	4.18	127.9
	2			6.56	130.0
	3			8.46	129.3
	4			10.40	124.8
3	1	4	58.8	3.77	127.4
	2			6.40	129.3
	3			8.33	129.8
	4			10.25	125.3
4	1	4	78.8	4.77	128.1
	2			6.56	129.9
	3			8.57	129.1
	4			10.39	124.9
5	1	6	131.4	4.82	129.3
	2			6.33	130.5
	3			7.34	131.8
	4			8.25	129.5
	5			10.34	125.4

Table 22

Compaction Test Data Summary

Tests On Minus 3/4-in. Fractions to Determine Procedures for Duplicating 6-in. Diameter Mold Test Results Using 12-in. Mold

GRADATION 1B, CLAY (CH) FINES, 10 PERCENT GRAVEL

TEST NO.	SPECIMEN NO.	HAMMER DIAMETER IN.	HAMMER WEIGHT LBS.	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
1	1	2	5.5	7.68	116.4
	2			9.64	122.2
	3	(6-IN. MOLD)		11.70	121.6
	4			13.40	118.2
	5			14.93	114.7
2	1	4	38.4	7.96	113.5
	2			9.61	119.2
	3			12.01	118.6
	4			13.33	118.3
3	1	4	58.8	7.14	115.9
	2			9.13	119.9
	3			10.54	121.9
	4			12.23	119.6
	5			13.70	118.8
4	1	4	78.8	8.92	118.3
	2			10.84	120.9
	3			11.29	121.8
	4			12.79	119.3
	5			15.13	114.4
5	1	6	131.4	8.73	119.5
	2			9.40	123.2
	3			10.92	123.5
	4			12.94	120.0
	5			14.95	114.9

Table 23

Compaction Test Data Summary

Tests On Minus 3/4-in. Fractions to Determine Procedures for Duplicating 6-in. Diameter Mold Test Results Using 12-in. Diameter Mold

GRADATION 3B, CLAY (CH) FINES, 40 PERCENT GRAVEL

TEST NO.	SPECIMEN NO.	HAMMER DIAMETER IN.	HAMMER WEIGHT LBS.	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
1	1	2	5.5	7.80	120.7
	2			8.03	122.3
	3			9.72	124.2
	4			10.34	122.5
	5	(6-IN. MOLD)		12.13	119.5
	6			12.50	119.4
	7			13.29	118.6
	8			13.57	117.9
	9			14.71	115.6
2	1	4	38.4	8.25	120.4
	2			9.43	122.8
	3			10.55	121.8
	4			11.87	119.0
3	1	4	58.8	6.82	121.2
	2			8.73	123.8
	3			10.59	122.5
	4			12.50	119.1
4	1	4	78.8	6.67	124.0
	2			9.33	122.8
	3			9.43	125.4
	4			10.43	123.2
5	1	6	131.4	8.86	123.4
	2			9.65	126.6
	3			10.77	125.2
	4			12.50	120.1

Table 24

Compaction Test Data Summary

Tests On Minus 3/4-in. Fractions to Determine Procedures for Duplicating 6-in. Diameter Mold Test Results Using 12-in. Diameter Mold

GRADATION 3B, SILT (ML) FINES, 40 PERCENT GRAVEL

TEST NO.	SPECIMEN NO.	HAMMER DIAMETER IN.	HAMMER WEIGHT LBS.	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
1	1	2	5.5	4.83	132.7
	2			5.82	132.3
	3	(6-IN. MOLD)		6.86	133.6
	4			6.88	134.6
	5			7.54	133.9
	6			8.66	132.4
	7			10.21	128.6
2	1	4	38.4	5.12	131.7
	2			6.50	135.0
	3			8.40	133.3
	4			9.99	129.9
3	1	4	58.8	4.83	131.8
	2			6.65	134.0
	3			6.72	134.5
	4			6.86	133.6
	5			8.24	132.8
	6			8.65	130.9
	7			10.35	126.6
4	1	4	78.8	4.72	132.2
	2			7.62	133.6
	3			9.05	130.8
5	1	6	131.4	5.29	132.3
	2			6.62	134.5
	3			8.74	131.0
	4			10.51	127.1

Table 25

Summary of Optimum Water Contents and Maximum Dry Unit Weights Tests On Minus 3/4-in. Fractions to Determine Procedures for Duplicating 6-in. Mold Test Results Using 12-in. Diameter Mold

HAMMER WEIGHT LBS	OPTIMUM WATER CONTENT PERCENT	MAXIMUM DRY UNIT WEIGHT PCF
	GRADATION 1B, 10 PERCENT GRAVEL	
	SILT (ML) FINES	
5.5	7.6	131.8
38.4	7.6	130.4
58.8	7.3	131.0
78.8	7.3	131.0
131.4	7.3	131.6

Range in optimum water content as a percent of mean value = 4.0 percent
Range in maximum dry unit weight as a percent of mean value = 1.1 percent

HAMMER WEIGHT LBS	OPTIMUM WATER CONTENT PERCENT	MAXIMUM DRY UNIT WEIGHT PCF
	CLAY (CH) FINES	
5.5	10.5	123.4
38.4	10.9	121.8
58.8	10.7	122.0
78.8	11.2	121.6
131.4	10.4	123.9

Range in optimum water content as a percent of mean value = 7.4 percent
Range in maximum dry unit weight as a percent of mean value = 1.9 percent

HAMMER WEIGHT LBS	OPTIMUM WATER CONTENT PERCENT	MAXIMUM DRY UNIT WEIGHT PCF
	GRADATION 3B, 40 PERCENT GRAVEL	
	SILT (ML) FINES	
5.5	7.5	134.3
38.4	6.9	135.3
58.8	7.2	133.8
78.8	7.2	134.2
131.4	7.0	134.3

Range in optimum water content as a percent of mean value = 8.4 percent
Range in maximum dry unit weight as a percent of mean value = 1.1 percent

HAMMER WEIGHT LBS	OPTIMUM WATER CONTENT PERCENT	MAXIMUM DRY UNIT WEIGHT PCF
	CLAY (CH) FINES	
5.5	9.8	123.7
38.4	9.7	122.5
58.8	9.7	124.3
78.8	9.2	125.7
131.4	9.9	126.6

Range in optimum water content as a percent of mean value = 7.3 percent
Range in maximum dry unit weight as a percent of mean value = 2.5 percent

Table 26

Compaction Test Data Summary

Tests On Minus 3/4-in. Fractions to Determine Procedure for Duplicating 6-in. Mold Test Results Using 18-in. Mold and 131.4 -lb Hammer

GRADATION 1B, 10 PERCENT GRAVEL

SILT (ML) FINES		CLAY (CH) FINES	
WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
4.43	130.3	7.92	120.5
5.38	131.1	9.22	121.9
7.92	130.0	11.30	121.9
8.05	130.3	10.31	122.9
10.09	125.2		

GRADATION 3B, 40 PERCENT GRAVEL

SILT (ML) FINES		CLAY (CH) FINES	
WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
4.50	132.4	8.54	123.7
6.16	134.2	10.24	124.1
8.52	131.0	10.60	124.1
10.07	126.6	11.64	120.3

Table 27

Optimum Water Contents and Maximum Dry Unit Weights Obtained From Tests Performed On Minus 3/4-in. Fractions in 6, 12, and 18-in Diameter Molds

OPTIMUM WATER CONTENT, PERCENT

MOLD DIAMETER IN.	GRADATION 1B, 10 PERCENT GRAVEL SILT (ML) FINES	GRADATION 1B, 10 PERCENT GRAVEL CLAY (CH) FINES	GRADATION 3B, 40 PERCENT GRAVEL SILT (ML) FINES	GRADATION 3B, 40 PERCENT GRAVEL CLAY (CH) FINES
6	7.6	10.5	7.5	9.8
12	7.3	10.3	7.0	9.9
18	7.3	10.4	7.0	9.8

RANGE IN VALUES AS PERCENT OF MEAN VALUE:

Gradation 1B, Silt Fines = 4.0 percent
Gradation 1B, Clay Fines = 1.9 percent
Gradation 3B, Silt Fines = 7.0 percent
Gradation 3B, Clay Fines = 5.0 percent

MAXIMUM DRY UNIT WEIGHT, PCF

MOLD DIAMETER IN.	GRADATION 1B, 10 PERCENT GRAVEL SILT (ML) FINES	GRADATION 1B, 10 PERCENT GRAVEL CLAY(CH) FINES	GRADATION 3B, 40 PERCENT GRAVEL SILT (ML) FINES	GRADATION 3B, 40 PERCENT GRAVEL CLAY (CH) FINES
6	131.8	123.4	134.3	123.7
12	131.6	125.6	134.3	126.6
18	131.6	122.9	134.6	125.0

RANGE IN VALUES AS PERCENT OF MEAN VALUE:

Gradation 1B, Silt Fines = 0.2 percent
Gradation 1B, Clay Fines = 2.2 percent
Gradation 3B, Silt Fines = 0.2 percent
Gradation 3B, Clay Fines = 2.3 percent

Table 28

Compaction Test Data Summary

Discrete Data for Tests Performed On Minus No. 4 Sieve Fractions Using Standard Procedure Developed for 12 and 18-in. Diameter Molds

6-in. Diameter Mold		12-in. Diameter Mold		18-in. Diameter Mold	
WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
SILT (ML) FINES, GRADATION 1C					
4.91	123.8	5.15	128.5	4.18	127.2
6.54	126.0	6.79	129.3	6.05	129.8
8.49	126.2	7.63	130.0	7.99	129.3
9.38	125.7	8.35	126.5	9.40	124.4
10.26	123.1	9.11	127.1		
10.75	123.0				
12.09	120.3				
12.13	120.7				
SILT (ML) FINES, GRADATION 3C					
4.51	115.8	7.29	120.4	8.99	122.1
4.60	114.8	10.29	122.4	10.61	122.3
5.62	117.6	10.06	122.7	12.89	117.1
6.60	118.1	12.34	118.6		
7.87	120.0				
8.49	119.5				
10.00	120.2				
10.57	121.2				
12.23	118.3				
12.36	117.7				
14.05	114.5				
CLAY (CH) FINES, GRADATION 1C					
8.31	109.0	7.83	117.0	10.13	120.2
10.34	114.9	10.57	122.8	12.15	120.1
10.35	114.6	11.67	123.2	14.10	116.6
12.37	118.1	14.12	117.2		
13.64	116.3				
14.51	115.7				
15.29	112.3				
16.05	112.2				
CLAY (CH) FINES, GRADATION 3C					
9.09	101.6	12.20	111.6	11.69	108.8
10.26	104.1	13.95	114.0	13.69	110.8
12.35	107.0	15.75	113.9	16.68	109.2
15.01	109.3	17.96	109.8		
17.07	108.3				
18.52	107.0				
18.65	106.5				
20.66	103.0				

Note: The specific gravity of the solids of the minus No. 4 fractions of Gradations 1B and 3B were 2.67 and 2.69, respectively

Table 29

Compaction Test Data Summary

Optimum Water Contents and Maximum Dry Unit Weights for Minus No.4

Fractions Tested in 12 and 18-in. Diameter Molds

MOLD DIAMETER IN.	OPTIMUM WATER CONTENT, PERCENT			
	1CML*	3CML*	1CCH*	3CCH*
6	7.7	10.6	12.7	15.2
12	7.4	10.0	11.2	14.6
18	6.9	10.0	11.2	14.2

RANGE IN VALUES AS PERCENT OF MEAN VALUE:
1CML = 10.9 percent
3CML = 5.9 percent
1CCH = 12.8 percent
3CCH = 4.0 percent

MOLD DIAMETER IN.	MAXIMUM DRY UNIT WEIGHT, PCF			
	1CML	3CML	1CCH	3CCH
6	127.2	121.2	118.2	109.5
12	130.0	122.8	123.6	114.7
18	130.5	122.8	121.3	111.2

RANGE IN VALUES AS PERCENT OF MEAN VALUE:
1CML = 2.6 percent
3CML = 1.3 percent
1CCH = 4.5 percent
3CCH = 4.6 percent

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*
1CML - - Gradation 1C, Silt (ML) Fines
3CML - - Gradation 3C, Silt (ML) Fines
1CCH - - Gradation 1C, Clay (CH) Fines
3CCH - - Gradation 3C, Clay (CH) Fines

Table 30

Discrete Data for Compaction Tests On Minus No.4 Materials

Performed in the 4-in. Diameter Mold

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 1C, Silt (ML) Fines	4.76	124.8
	6.23	126.0
	8.47	128.4
	10.75	123.7
	12.82	120.9
No. 1C, Clay (CH) Fines	7.56	110.2
	9.75	116.1
	11.84	119.2
	13.16	118.2
	15.54	113.7
No. 3C, Silt (ML) Fines	5.98	116.9
	7.84	118.2
	9.87	120.3
	11.85	119.8
	13.68	115.5
No. 3C, Clay (CH) Fines	11.29	107.5
	12.87	108.0
	15.01	113.4
	17.54	109.8
	20.05	104.9

NOTE: See Table 19 for description of gradations

Table 31

Compaction Test Data Summary

Minus No.4 Gradations Tested in 4 and 6-in. Diameter Molds

GRADATION	OPTIMUM WATER CONTENT PERCENT MOLD DIAMETER 4-IN.	6-IN.	MAXIMUM DRY UNIT WEIGHT PCF MOLD DIAMETER 4-IN.	6-IN.
No. 1C, Silt (ML) Fines	8.1	7.7	128.5	127.2
No. 1C, Clay (CH) Fines	12.2	12.7	119.5	118.2
No. 3C, Silt (ML) Fines	11.0	10.6	121.2	121.2
No. 3C, Clay (CH) Fines	15.0	15.2	113.4	109.5

NOTE: See Table 19 for description of gradations

Table 32

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 1 With Silt (ML) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 1: Minus 3-in. Full-Scale	4.22	135.9
18-in. Diameter Mold	4.93	137.6
	5.07	138.3
	6.02	138.6
	7.34	134.6
No. 1A: Minus 2-in.	3.58	131.6
12-in. Diameter Mold	5.18	135.1
	5.35	135.5
	6.08	134.0
	6.29	135.6
	7.42	133.7
	7.96	132.7
	8.17	132.3
	8.28	130.7
No. 1B: Minus 3/4-in.	4.61	128.9
6-in. Diameter Mold	6.40	129.9
	6.60	131.5
	6.94	131.4
	8.40	131.0
	10.21	128.9
No. 1C: Minus No.4	4.91	123.8
6-in. Diameter Mold	6.54	126.0
	8.49	126.2
	9.38	125.7
	10.26	123.1
	10.75	123.0
	12.09	120.3
	12.13	120.7

NOTE: See Table 19 for description of gradations

Table 33

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 2 With Silt (ML) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 2: Minus 3-in. Full-Scale	3.15	142.4
18-in. Diameter Mold	3.54	141.6
	4.26	141.8
	5.40	141.8
	6.23	139.2
No. 2A: Minus 2-in.	4.22	135.6
12-in. Diameter Mold	5.16	138.0
	6.31	139.2
	6.41	136.9
	7.23	135.5
	7.31	135.8
	8.03	134.7
	8.29	133.6
No. 2B: Minus 3/4-in.	4.61	128.9
6-in Diameter Mold	6.40	129.9
	6.60	131.5
(Same fraction as for full-scale	6.94	131.4
Gradation No. 1, Table 33)	8.40	131.0
	10.21	128.9
No. 2C: Minus No.4	4.91	123.8
6-in Diameter Mold	6.54	126.0
	8.49	126.2
(Same fraction as for full-scale	9.38	125.7
Gradation No. 1, Table 33)	10.26	123.1
	10.75	123.0
	12.09	120.3
	12.13	120.7

NOTE: See Table 19 for description of gradations

Table 34

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 3 With Silt (ML) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 3: Minus 3-in. Full-Scale	4.58	137.5
18-in. Diameter Mold	4.89	138.9
	5.77	139.2
	6.97	138.0
No. 3A: Minus 2-in.	4.36	137.2
12-in. Diameter Mold	5.33	136.0
	5.63	137.8
	5.64	137.7
	5.88	136.3
	6.72	138.2
	6.75	137.7
	6.86	137.2
	7.09	138.2
	7.92	135.0
	8.80	133.0
	9.00	132.8
No. 3B: Minus 3/4-in.	4.83	132.7
6-in. Diameter Mold	5.82	132.3
	6.86	133.6
	6.88	134.6
	7.54	133.9
	8.66	132.4
	10.21	128.6
No. 3C: Minus No.4	4.51	115.8
6-in. Diameter Mold	4.60	114.8
	5.62	117.6
	6.60	118.1
	7.87	120.0
	8.49	119.5
	10.00	120.2
	10.57	121.2
	12.23	118.3
	12.36	117.7
	14.05	114.5

NOTE: See Table 19 for description of gradations

Table 35

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 4 With Silt (ML) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 4: Minus 3-in. Full-Scale	3.27	141.7
18-in. Diameter Mold	4.36	141.9
	5.37	141.9
	6.50	139.9
	8.40	135.6
No. 4A: Minus 2-in.	2.67	138.3
12-in. Diameter Mold	4.71	140.6
	4.90	140.3
	5.80	140.4
	6.23	138.8
	6.63	140.1
	6.93	139.4
	8.23	137.5
No. 3B: Minus 3/4-in.	4.83	132.7
6-in. Diameter Mold	5.82	132.3
	6.86	133.6
(Same fraction as for full-scale	6.88	134.6
Gradation No. 3, Table 35)	7.54	133.9
	8.66	132.4
	10.21	128.6
No. 3C: Minus No.4	4.51	115.8
6-in. Diameter Mold	4.60	114.8
	5.62	117.6
	6.60	118.1
(Same fraction as for full-scale	7.87	120.0
Gradation No. 3, Table 35)	8.49	119.5
	10.00	120.2
	10.57	121.2
	12.23	118.3
	12.36	117.7
	14.05	114.5

NOTE: See Table 19 for description of gradations

Table 36

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 1 With Clay (CH) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 1: Minus 3-in. Full-Scale	6.55	126.8
18-in. Diameter Mold	7.31	129.4
	7.92	130.6
	9.04	130.2
	9.47	129.1
	11.20	126.0
No. 1A: Minus 2-in.	4.66	120.1
12-in. Diameter Mold	5.50	124.8
	6.20	125.2
	6.39	127.4
	7.20	130.8
	8.11	130.2
	8.18	129.1
	9.23	129.5
	10.22	128.2
	10.46	127.7
	11.84	124.7
No. 1B: Minus 3/4-in.	7.68	116 4
6-in. Diameter Mold	9.64	122.2
	11.70	121.6
	13.40	118.2
	14.93	114.7
No. 1C: Minus No.4	8.31	109.0
6-in. Diameter Mold	10.34	114.9
	10.35	114.6
	12.37	118.1
	13.64	116.3
	14.51	115.7
	15.29	112.3
	16.05	112.2

NOTE: See Table 19 for description of gradations

Table 37

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 2 With Clay (CH) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 2: Minus 3-in. Full-Scale	4.37	132.9
18-in. Diameter Mold	5.39	135.1
	6.50	137.6
	7.56	136.3
	8.09	132.4
	9.23	129.6
No. 2A: Minus 2-in.	5.46	123.4
12-in. Diameter Mold	6.61	128.9
	6.98	133.1
	7.37	131.2
	8.10	133.5
	9.01	131.3
	9.29	131.4
	10.17	128.9
No. 1B: Minus 3/4-in.	7.68	116.4
6-in. Diameter Mold	9.64	122.2
	11.70	121.6
(Same fraction as for full-scale	13.40	118.2
Gradation No. 1, Table 37)	14.93	114.7
No. 1C: Minus No. 4	8.31	109.0
6-in. Diameter Mold	10.34	114.9
	10.35	114.6
	12.37	118.1
(Same fraction as for full-scale	13.64	116.3
Gradation No.1, Table 37)	14.51	115.7
	15.29	112.3
	16.05	112.2

NOTE: See Table 19 for description of gradations

Table 38

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 3 With Clay (CH) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 3: Minus 3-in. Full-Scale	5.17	128.5
18-in. Diameter Mold	6.30	130.0
	7.73	129.8
	8.38	128.7
	10.48	123.1
No. 3A: Minus 2-in.	5.84	126.5
12-in. Diameter Mold	6.73	128.5
	7.68	130.9
	9.54	129.4
	10.85	126.6
No. 3B: Minus 3/4-in.	6.34	122.0
6-in. Diameter Mold	7.80	120.7
	8.03	122.3
	9.72	124.2
	10.34	122.5
	12.13	119.5
	12.50	119.4
	13.29	118.6
	13.57	117.9
	14.71	115.6
No. 3C: Minus No.4	9 09	101.6
6-in. Diameter Mold	10.26	104.1
	12.35	107.0
	13.19	109.2
	14.46	111.2
	15.01	109.3
	17.07	108.3
	18.52	107.0
	18.65	106.5
	20.66	103.0

NOTE: See Table 19 for description of gradations

Table 39

Discrete Data for Compaction Tests On Successively Scalped Fractions of Gradation No. 4 With Clay (CH) Fines

GRADATION	WATER CONTENT PERCENT	DRY UNIT WEIGHT PCF
No. 4: Minus 3-in. Full-Scale	4.29	131.0
18-in. Diameter Mold	4.44	129.0
	5.55	133.3
	6.38	134.8
	6.48	135.0
	6.62	134.4
	7.56	133.8
	8.56	131.3
	10.77	126.1
No. 4A: Minus 2-in.	4.20	127.2
12-in. Diameter Mold	6.27	131.8
	6.94	135.6
	7.03	135.8
	7.84	134.6
	8.13	134.6
	8.76	132.7
	9.24	126.7
	9.82	127.0
	10.32	125.7
	11.12	124.7
No. 3B: Minus 3/4-in.	6.34	122.0
6-in. Diameter Mold	7.80	120.7
	8.03	122.3
	9.72	124.2
(Same fraction as for full-scale	10.34	122.5
Gradation No. 3, Table 39)	12.13	119.5
	12.50	119.4
	13.29	118.6
	13.57	117.9
	14.71	115.6
No. 4C: Minus No.4	9.09	101.6
6-in. Diameter Mold	10.26	104.1
	12.35	107.0
	13.19	109.2
(Same fraction as for full-scale	14.46	111.2
Gradation No. 3, Table 39)	15.01	109.3
	17.07	108.3
	18.52	107.0
	18.65	106.5
	20.66	103.0

NOTE: See Table 19 for description of gradations

Table 40

Maximum Dry Unit Weights and Optimum Water Contents for Compaction Tests On Successively Scalped Fractions

MAXIMUM PARTICLE SIZE, IN.	MAXIMUM DRY UNIT WEIGHT, PCF GRADATION NO.1	GRADATION NO.2	GRADATION NO.3	GRADATION NO.4
SILT (ML) FINES				
3	139.0	142.5	139.4	142.2
2	135.0	138.5	139.2	140.7
3/4	131.8	131.8	134.3	134.3
NO.4 SIEVE	127.2	127.2	121.2	121.2
CLAY (CH) FINES				
3	130.6	137.8	130.3	134.9
2	130.6	133.1	131.7	135.8
3/4	123.4	123.4	123.7	123.7
NO.4 SIEVE	118.2	118.2	109.5	109.5

MAXIMUM PARTICLE SIZE, IN.	OPTIMUM WATER CONTENT, PERCENT GRADATION NO.1	GRADATION NO.2	GRADATION NO.3	GRADATION NO.4
SILT (ML) FINES				
3	5.6	4.9	5.6	5.4
2	5.9	5.3	6.3	5.6
3/4	7.6	7.6	7.5	7.5
NO.4 SIEVE	7.7	7.7	10.6	10.6
CLAY (CH) FINES				
3	8.4	6.9	7.3	6.8
2	8.4	8.0	8.2	7.4
3/4	10.5	10.5	9.8	9.8
NO.4 SIEVE	12.7	12.7	15.2	15.2

Table 41

Summary of Maximum Permissible Degrees of Scalping to Obtain Maximum Dry Unit Weights of Parent Gradations From Those of Fractions

	PERMISSIBLE SCALPING IN PERCENT BY WEIGHT*			
	SILT (ML) GRADATION	FINES %	CLAY (CH) GRADATION	FINES %
PARENT GRADATION: MINUS 3-IN.	1	9	1	8
	2	14	2	13
	3	10	3	11
	4	18	4	20
PARENT GRADATION: MINUS 2-IN.	1	8	1	4
	2	12	2	7
	3	10	3	6
	4	19	4	9
PARENT GRADATION: MINUS 3/4-IN.				
Minus No.4 Fractions Identical for Gradations 1 and 2 and for Gradations 3 and 4		3		5

* A maximum permissible deviation of fraction maximum dry unit weight from "parent" gradation maximum dry unit weight of minus 2.5 lb/cu ft was used to determine maximum allowable scalping. This deviation represented about two percent of the average maximum dry unit of the parent gradations containing plus No.4 material.

Table 42

Summary of Maximum Permissible Degrees of Scalping to Obtain Optimum Water Contents of Parent Gradations From Those of Fractions

	PERMISSIBLE SCALPING IN PERCENT BY WEIGHT*			
	SILT (ML) GRADATION	FINES %	CLAY (CH) GRADATION	FINES %
PARENT GRADATION: MINUS 3-IN.	1	9.5	1	10
	2	11	2	17
	3	7	3	8
	4	14	4	18
PARENT GRADATION: MINUS 2-IN.	1	6	1	4.5
	2	8	2	11.3
	3	10.5	3	15.5
	4	17	4	22
PARENT GRADATION: MINUS 3/4-IN.				
Minus No.4 Fractions Identical for Gradations 1 and 2 and for Gradations 3 and 4		2.5		7

* A maximum permissible deviation of fraction optimum water content from "parent" gradation optimum water content of minus 0.7 percentage points was used to determine maximum allowable scalping. This deviation represented about ten percent of the average optimum water content of the parent gradations containing plus No.4 material.

Table 43

Prediction of Maximum Dry Unit Weight

Data Corrected for Equipment Size Effects

Gradation No.	Percent Oversize	Max Density Fine Fraction pcf	Predicted Density, Total Material pcf	Actual Max. Density, Total Material pcf	Predicted Minus Actual pcf
PLUS NO. 4 OVERSIZE, SILT (ML) FINES					
1	28	130.5	139.0	139.0	0.0
1A	20.9	130.0	136.3	135.0	1.3
2	46	130.5	145.2	142.5	2.7
2A	31.2	130.0	139.7	138.5	1.2
3	52	122.8	142.5	139.4	3.1
3A	51	122.8	142.0	139.2	2.8
4	64	122.8	148.0	142.2	5.8
4A	61.5	122.8	146.8	140.7	6.1
PLUS NO. 4 OVERSIZE, CLAY (CH) FINES					
1	28	121.3	131.4	130.6	0.8
1A	20.9	123.6	130.7	130.6	0.1
2	46	121.3	138.8	137.8	1.0
2A	31.2	123.6	134.6	133.1	1.5
3	52	111.2	134.7	130.3	4.4
3A	51	114.7	136.6	131.7	4.9
4	64	111.2	141.6	134.9	6.7
4A	61.5	114.7	142.2	135.8	6.4
PLUS 3/4-IN. OVERSIZE, SILT (ML) FINES					
1	20	131.6	137.5	139.0	-1.5
1A	12	131.6	135.0	135.0	0.0
2	40	131.6	143.9	142.5	1.4
2A	23.6	131.6	138.6	138.8	-0.2
3	20	134.6	140.1	139.4	0.7
3A	18.4	134.3	139.3	139.2	0.1
4	40	134.6	146.0	142.2	3.8
4A	35.8	134.3	144.5	140.7	3.8
PLUS 3/4-IN. OVERSIZE, CLAY (CH) FINES					
1	20	122.9	129.8	130.6	-0.8
1A	12	125.6	129.5	130.6	-1.1
2	40	122.9	137.5	137.8	-0.3
2A	23.6	125.6	133.4	133.1	0.3
3	20	125.0	131.6	130.3	1.3
3A	18.4	126.6	132.5	131.7	0.8
4	40	125.0	139.0	134.9	4.1
4A	35.8	126.6	138.7	135.8	2.9

Note: Bulk specific gravity of oversized particles (gravel) = 2.68

Table 44

Predictions of Maximum Dry Unit Weight and Optimum Water Content

For Minus 3/4-in. Gradations From Those of Minus No.4 Gradations

Data Corrected for Equipment Size Effects

Gradation No.	Percent Oversize	Max Density Fine Fraction pcf	Predicted Density, Total Material pcf	Actual Max. Density, Total Material pcf	Predicted Minus Actual pcf
SILT (ML) FINES					
1B	10	127.2	130.3	131.8	-1.5
3B	40	121.2	136.2	134.3	1.9
CLAY (CH) FINES					
1B	10	118.2	121.8	123.4	-1.6
3B	40	109.5	127.0	123.7	3.3

Gradation No.	Percent Oversize	Opt. Water Content Fine Fraction %	Predicted Opt. Water Content, Total Material %	Actual Opt. Water Content, Total Material %	Predicted Minus Actual %
SILT (ML) FINES					
1B	10	7.7	7.0	7.6	-0.6
3B	40	10.6	6.6	7.5	-0.9
CLAY (CH) FINES					
1B	10	12.7	11.5	10.5	1.0
3B	40	15.2	9.4	9.8	-0.4

Note: Tests performed in 6-in. diameter mold

Table 45

Prediction of Optimum Water Content

Data Corrected for Equipment Size Effects

Gradation No.	Percent Oversize	Opt. Water Content Fine Fraction percent	Predicted Opt. Water Content, Total Material percent	Actual Opt. Water Content, Total Material percent	Predicted Minus Actual percent
PLUS NO. 4 OVERSIZE, SILT (ML) FINES					
1	28	6.9	5.1	5.6	-0.5
1A	20.9	7.4	6.0	5.9	0.1
2	46	6.9	4.0	4.9	-0.9
2A	31.2	7.4	5.3	5.3	0.0
3	52	10.0	5.1	5.6	-0.5
3A	51	10.0	5.2	6.3	-1.1
4	64	10.0	4.0	5.4	-1.4
4A	61.5	10.0	4.2	5.6	-1.4
PLUS NO. 4 OVERSIZE, CLAY (CH) FINES					
1	28	11.2	8.2	8.4	-0.2
1A	20.9	11.2	9.0	8.4	0.6
2	46	11.2	6.3	6.9	-0.6
2A	31.2	11.2	7.9	8.0	-0.1
3	52	14.2	7.1	7.3	-0.2
3A	51	14.6	7.5	8.2	-0.7
4	64	14.2	5.5	6.8	-1.3
4A	61.5	14.6	6.0	7.4	-1.4
PLUS 3/4-IN. OVERSIZE, SILT (ML) FINES					
1	20	7.3	6.0	5.6	0.4
1A	12	7.3	6.5	5.9	0.6
2	40	7.3	4.6	4.9	-0.3
2A	23.6	7.3	5.7	5.3	0.4
3	20	7.0	5.7	5.6	0.1
3A	18.4	7.0	5.8	6.3	-0.5
4	40	7.0	4.4	5.4	-1.0
4A	35.8	7.0	4.7	5.6	-0.9
PLUS 3/4-IN. OVERSIZE, CLAY (CH) FINES					
1	20	10.4	8.4	8.4	0.0
1A	12	10.3	9.1	8.4	0.7
2	40	10.4	6.5	6.9	-0.4
2A	23.6	10.3	8.0	8.0	0.0
3	20	9.8	8.0	7.3	0.7
3A	18.4	9.9	8.2	8.2	0.0
4	40	9.8	6.1	6.8	-0.7
4A	35.8	9.9	6.6	7.4	-0.8

Note: Water content of oversize (gravel) = 0.6 percent (air-dry)

Table 46

Prediction of Maximum Dry Unit Weight

Data Not Corrected for Equipment Size Effects

Gradation No.	Percent Oversize	Max Density Fine Fraction pcf	Predicted Density, Total Material pcf	Actual Max. Density, Total Material pcf	Predicted Minus Actual pcf
PLUS NO. 4 OVERSIZE, SILT (ML) FINES					
1	28	127.2	136.3	139.0	-2.7
1A	20.9	127.2	133.9	135.0	-1.1
2	46	127.2	142.9	142.5	0.4
2A	31.2	127.2	137.5	138.5	-1.0
3	52	121.2	141.4	139.4	2.0
3A	51	121.2	141.0	139.2	1.8
4	64	121.2	147.1	142.2	4.9
4A	61.5	121.2	145.9	140.7	5.2
PLUS NO. 4 OVERSIZE, CLAY (CH) FINES					
1	28	118.2	128.8	130.6	-1.8
1A	20.9	118.2	125.9	130.6	-4.7
2	46	118.2	136.6	137.8	-1.2
2A	31.2	118.2	130.1	133.1	-3.0
3	52	109.5	133.5	130.3	3.2
3A	51	109.5	132.9	131.7	1.2
4	64	109.5	140.6	134.9	5.7
4A	61.5	109.5	139.0	135.8	3.2
PLUS 3/4-IN. OVERSIZE, SILT (ML) FINES					
1	20	131.8	137.6	139.0	-1.4
1A	12	131.8	135.2	135.0	0.2
2	40	131.8	144.0	142.5	1.5
2A	23.6	131.8	138.7	138.8	-0.1
3	20	134.3	139.8	139.4	0.4
3A	18.4	134.3	139.3	139.2	0.1
4	40	134.3	145.8	142.2	3.6
4A	35.8	134.3	144.5	140.7	3.8
PLUS 3/4-IN. OVERSIZE, CLAY (CH) FINES					
1	20	123.4	130.2	130.6	-0.4
1A	12	123.4	127.4	130.6	-3.2
2	40	123.4	137.8	137.8	0.0
2A	23.6	123.4	131.5	133.1	0.4
3	20	123.7	130.5	130.3	0.2
3A	18.4	123.7	129.9	131.7	-1.8
4	40	123.7	138.1	134.9	3.2
4A	35.8	123.7	136.4	135.8	0.6

Note: Bulk specific gravity of oversized particles (gravel) = 2.68

Table 47

Prediction of Optimum Water Content

Data Not Corrected for Equipment Size Effects

Gradation No.	Percent Oversize	Opt. Water Content Fine Fraction percent	Predicted Opt. Water Content, Total Material percent	Actual Opt. Water Content, Total Material percent	Predicted Minus Actual percent
PLUS NO. 4 OVERSIZE, SILT (ML) FINES					
1	28	7.7	5.7	5.6	0.1
1A	20.9	7.7	6.2	5.9	0.3
2	46	7.7	4.4	4.9	-0.5
2A	31.2	7.7	5.5	5.3	0.2
3	52	10.6	5.4	5.6	-0.2
3A	51	10.6	5.5	6.3	-0.8
4	64	10.6	4.2	5.4	-1.2
4A	61.5	10.6	4.4	5.6	-1.2
PLUS NO. 4 OVERSIZE, CLAY (CH) FINES					
1	28	12.7	9.3	8.4	0.9
1A	20.9	12.7	10.2	8.4	1.8
2	46	12.7	7.1	6.9	0.2
2A	31.2	12.7	8.9	8.0	0.9
3	52	15.2	7.6	7.3	0.3
3A	51	15.2	7.8	8.2	-0.4
4	64	15.2	5.9	6.8	-0.9
4A	61.5	15.2	6.2	7.4	-1.2
PLUS 3/4-IN. OVERSIZE, SILT (ML) FINES					
1	20	7.6	6.2	5.6	0.6
1A	12	7.6	6.8	5.9	0.9
2	40	7.6	4.8	4.9	-0.1
2A	23.6	7.6	5.9	5.3	0.6
3	20	7.5	6.1	5.6	0.5
3A	18.4	7.5	6.2	6.3	-0.1
4	40	7.5	4.7	5.4	-0.7
4A	35.8	7.5	5.0	5.6	-0.6
PLUS 3/4-IN. OVERSIZE, CLAY (CH) FINES					
1	20	10.5	8.5	8.4	0.1
1A	12	10.5	9.3	[illegible]4	0.9
2	40	10.5	6.5	6.9	-0.4
2A	23.6	10.5	8.2	8.0	0.2
3	20	9.8	8.0	7.3	0.7
3A	18.4	9.8	8.1	8.2	-0.1
4	40	9.8	6.1	6.8	-0.7
4A	35.8	9.8	6.5	7.4	-0.9

Note: Water content of oversize (gravel) = 0.6 percent (air-dry)

Table 48

Fraction Density Factors

Minus 3-in. Gradations, Data Corrected for Equipment Size Effects

GRADATION	c	f	γ_{tmax}	γ_f	γ_{fmax}	r
			FINE FRACTION = MINUS NO.4			
MINUS 3-IN., SILT FINES						
1	0.28	0.72	139.0	130.4	130.5	1.00
2	0.46	0.54	142.5	126.5	130.5	0.97
3	0.52	0.48	139.4	118.1	122.8	0.96
4	0.64	0.36	142.2	112.3	122.8	0.92
MINUS 3-IN., CLAY FINES						
1	0.28	0.72	130.6	120.4	121.3	0.99
2	0.46	0.54	137.8	119.8	121.3	0.99
3	0.52	0.48	130.3	105.1	111.2	0.95
4	0.64	0.36	134.9	100.4	111.2	0.90
			FINE FRACTION = MINUS 3/4-IN.			
MINUS 3-IN., SILT FINES						
1	0.20	0.80	139.0	133.4	131.6	1.01
2	0.40	0.60	142.5	129.7	131.6	0.99
3	0.20	0.80	139.4	133.8	134.6	0.99
4	0.40	0.60	142.2	129.3	134.6	0.96
MINUS 3-IN., CLAY FINES						
1	0.20	0.80	130.6	123.8	122.9	1.01
2	0.40	0.60	137.8	123.3	122.9	1.00
3	0.20	0.80	130.3	123.5	125.0	0.99
4	0.40	0.60	134.9	119.5	125.0	0.96

c = percent by weight of coarse fraction expressed as decimal

f = percent by weight of fine fraction expressed as decimal

γ_{tmax} = maximum dry unit weight of the total material

γ_f = calculated dry unit weight of fine fraction in the total material using Equation (1), pcf

γ_{fmax} = maximum dry unit weight of the fine fraction obtained in 18-in. diameter mold, pcf

r = interference coefficient or γ_f / γ_{fmax}

Table 49

Fraction Density Factors

Minus 2-in. Gradations, Data Corrected for Equipment Size Effects

GRADATION	c	f	γ_{tmax}	γ_f	γ_{fmax}	r
			FINE FRACTION = MINUS NO.4			
MINUS 2-IN., SILT FINES						
1A	0.209	0.791	135.0	128.5	130.0	0.99
2A	0.312	0.688	138.5	128.5	130.0	0.99
3A	0.51	0.49	139.2	118.5	122.8	0.96
4A	0.615	0.385	140.7	112.2	122.8	0.91
MINUS 2-IN., CLAY FINES						
1A	0.209	0.791	130.6	123.4	123.6	1.00
2A	0.312	0.688	133.1	121.8	123.6	0.99
3A	0.51	0.49	131.7	107.8	114.7	0.94
4A	0.615	0.385	135.8	104.4	114.7	0.91
			FINE FRACTION = MINUS 3/4-IN.			
MINUS 2-IN., SILT FINES						
1A	0.12	0.88	135.0	131.5	131.6	1.00
2A	0.236	0.764	138.8	131.9	131.6	1.00
3A	0.184	0.816	139.2	134.1	134.3	1.00
4A	0.358	0.642	140.7	129.3	134.3	0.96
MINUS 2-IN., CLAY FINES						
1A	0.12	0.88	130.6	126.8	125.6	1.01
2A	0.236	0.764	133.1	125.2	125.6	1.00
3A	0.184	0.816	131.7	125.7	126.6	0.99
4A	0.358	0.642	135.8	122.9	126.6	0.97

c = percent by weight of coarse fraction expressed as decimal

f = percent by weight of fine fraction expressed as decimal

γ_{tmax} = maximum dry unit weight of the total material, pcf

γ_f = calculated dry unit weight of fine fraction in the total material using Equation (1), pcf

γ_{fmax} = maximum dry unit weight of the fine fraction obtained in the 12-in. diameter mold, pcf

r = interference coefficient or γ_f / γ_{fmax}

Table 50

Fraction Density Factors

Minus 3-in. Gradations, Data Not Corrected for Equipment Size Effects

GRADATION	c	f	γ_{tmax}	γ_f	γ_{fmax}	r
			FINE FRACTION = MINUS NO.4			
MINUS 3-IN., SILT FINES						
1	0.28	0.72	139.0	130.4	127.2	1.025
2	0.46	0.54	142.5	126.5	127.2	0.99
3	0.52	0.48	139.4	118.1	121.2	0.97
4	0.64	0.36	142.2	112.3	121.2	0.93
MINUS 3-IN., CLAY FINES						
1	0.28	0.72	130.6	120.4	118.2	1.02
2	0.46	0.54	137.8	119.8	118.2	0.99
3	0.52	0.48	130.3	105.1	110.0	0.96
4	0.64	0.36	134.9	100.4	110.0	0.91
			FINE FRACTION = MINUS 3/4-IN.			
MINUS 3-IN., SILT FINES						
1	0.20	0.80	139.0	133.4	131.8	1.01
2	0.40	0.60	142.5	129.7	131.8	0.98
3	0.20	0.80	139.4	133.8	134.3	0.99
4	0.40	0.60	142.2	129.3	134.3	0.96
MINUS 3-IN., CLAY FINES						
1	0.20	0.80	130.6	123.8	123.4	1.00
2	0.40	0.60	137.8	123.3	123.4	1.00
3	0.20	0.80	130.3	123.5	123.7	1.00
4	0.40	0.60	134.9	119.5	123.7	0.97

c = percent by weight of coarse fraction expressed as decimal

f = percent by weight of fine fraction expressed as decimal

γ_{tmax} = maximum dry unit weight of the total material, pcf

γ_f = calculated dry unit weight of fine fraction in the total material using Equation (1), pcf

γ_{fmax} = maximum dry unit weight of the fine fraction obtained in the 6-in. diameter mold, pcf

r = interference coefficient or γ_f / γ_{fmax}

Table 51

Fraction Density Factors

Minus 2-in. Gradations, Data Not Corrected for Equipment Size Effects

GRADATION	c	f	γ_{tmax}	γ_f	γ_{fmax}	r
			FINE FRACTION = MINUS NO.4			
MINUS 2-IN., SILT FINES						
1A	0.209	0.791	135.0	128.5	127.2	1.01
2A	0.312	0.688	138.5	128.5	127.2	1.01
3A	0.51	0.49	139.2	118.5	121.2	0.98
4A	0.615	0.385	140.7	112.2	121.2	0.93
MINUS 2-IN., CLAY FINES						
1A	0.209	0.791	130.6	123.4	118.2	1.04
2A	0.312	0.688	133.1	121.8	118.2	1.03
3A	0.51	0.49	131.7	107.8	110.0	0.98
4A	0.615	0.385	135.8	104.4	110.0	0.95
			FINE FRACTION = MINUS 3/4-IN.			
MINUS 2-IN., SILT FINES						
1A	0.12	0.88	135.0	131.5	131.8	1.01
2A	0.236	0.764	138.8	131.9	131.8	1.00
3A	0.184	0.816	139.2	134.1	134.3	1.00
4A	0.358	0.642	140.7	129.3	134.3	0.96
MINUS 2-IN., CLAY FINES						
1A	0.12	0.88	130.6	126.8	123.4	1.03
2A	0.236	0.764	133.1	125.2	123.4	1.02
3A	0.184	0.816	131.7	125.7	123.7	1.02
4A	0.358	0.642	135.8	122.9	123.7	0.99

c = percent by weight of coarse fraction expressed as decimal

f = percent by weight of fine fraction expressed as decimal

γ_{tmax} = maximum dry unit weight of the total material, pcf

γ_f = calculated dry unit weight of fine fraction in the total material using Equation (1), pcf

γ_{fmax} = maximum dry unit weight of the fine fraction obtained in the 6-in. diameter mold, pcf

r = interference coefficient or γ_f / γ_{fmax}

Table 52

Comparison of Calculated Values of Dry Unit Weight of the Total Material Using Fraction Density Factors of WES, USBR, AASHTO and NAVFAC

GRADATION	FRACTION DENSITY FACTORS				CALCULATED MAXIMUM DRY UNIT WEIGHT OF THE TOTAL MATERIAL, PCF†			
	WES	USBR	AASHTO*	NAVFAC**	WES††	USBR	AASHTO	NAVFAC
				FINE FRACTION IS MINUS NO.4				
MINUS 3-IN., SILT FINES								
1	1.02	1.00	0.98	0.98	139.0	135.9	134.2	133.4
2	0.99	0.95	0.94	0.96	142.5	138.8	138.0	137.9
3	0.97	0.93	0.92	0.96	139.4	136.0	135.1	135.8
4	0.93	0.88	0.85	0.93	142.2	139.1	136.9	139.9
MINUS 3-IN., CLAY FINES								
1	1.02	1.02	0.98	0.98	130.6	130.4	126.7	126.1
2	0.99	0.96	0.94	0.96	137.8	133.4	131.7	131.9
3	0.96	0.94	0.92	0.96	130.3	129.0	127.6	128.6
4	0.91	0.88	0.85	0.93	134.9	133.0	130.6	134.0
MINUS 2-IN., SILT FINES								
1A	1.01	1.02	0.99	0.99	135.0	136.1	132.8	131.8
2A	1.01	1.00	0.97	0.98	138.5	138.0	134.4	134.2
3A	0.98	0.94	0.93	0.96	139.2	136.0	135.2	135.5
4A	0.93	0.90	0.87	0.93	140.7	138.8	136.4	139.0
MINUS 2-IN., CLAY FINES								
1A	1.04	1.00	0.99	0.99	130.6	125.9	124.8	124.0
2A	1.03	0.99	0.97	0.98	133.1	129.1	127.1	127.1
3A	0.98	0.94	0.93	0.96	131.7	128.4	127.6	128.2
4A	0.95	0.95	0.87	0.94	135.8	135.8	129.9	132.8

* The average value of the AASHTO range in fraction density factor is used

** The equivalent fraction density factor is used for the NAVFAC case

† All calculated values use the maximum dry unit weights of WES minus No.4 fractions obtained in the 6-in. mold

†† The WES calculated values of dry unit weight of the total materials are equal to the actual values of the maximum dry unit weight because the WES fraction density factors were derived from those values.

Table 53

Corrected Density Interference Coefficients

Based on the Minus No.4 Fraction*

SILT (ML) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1B	3/4-in.	10	128.8	127.2	2.68	3.778
1A	2-in.	20.9	128.4	130.0	2.68	1.764
1	3-in.	28	130.4	130.5	2.68	1.332
2A	2-in.	31.2	128.5	130.0	2.68	1.182
3B	3/4-in.	40	118.6	121.2	2.68	0.913
2	3-in.	46	126.6	130.5	2.68	0.787
3A	2-in.	51	118.5	122.8	2.68	0.706
3	3-in.	52	118.1	122.8	2.68	0.690
4A	2-in.	61.5	112.1	122.8	2.68	0.554
4	3-in.	64	112.0	122.8	2.68	0.532

CLAY (CH) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1B	3/4-in.	10	119.9	118.2	2.68	3.785
1A	2-in.	20.9	123.4	123.6	2.68	1.782
1	3-in.	28	120.3	121.3	2.68	1.322
2A	2-in.	31.2	121.7	123.6	2.68	1.178
3B	3/4-in.	40	105.4	109.5	2.68	0.898
2	3-in.	46	119.8	121.3	2.68	0.801
3A	2-in.	51	107.8	114.7	2.68	0.688
3	3-in.	52	105.1	111.2	2.68	0.678
4A	2-in.	61.5	98.7	114.7	2.68	0.522
4	3-in.	64	100.3	111.2	2.68	0.526

* Maximum dry unit weight of the minus No.4 fraction determined in same size mold as for the total material (see Table 25)

** γ_f of the minus No.4 fraction determined from Equation (1) using the maximum dry unit weight of the total material

Table 54

Uncorrected Density Interference Coefficients

Based on the Minus No.4 Fraction*

SILT (ML) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1B	3/4-in.	10	128.8	127.2	2.68	3.778
1A	2-in.	20.9	128.5	127.2	2.68	1.804
1	3-in.	28	130.4	127.2	2.68	1.366
2A	2-in.	31.2	128.5	127.2	2.68	1.208
3B	3/4-in.	40	118.6	121.2	2.68	0.913
2	3-in.	46	126.5	127.2	2.68	0.807
3A	2-in.	51	118.4	121.2	2.68	0.715
3	3-in.	52	118.1	121.2	2.68	0.699
4A	2-in.	61.5	112.3	121.2	2.68	0.562
4	3-in.	64	112.0	121.2	2.68	0.539

CLAY (CH) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1B	3/4-in.	10	119.9	118.2	2.68	3.785
1A	2-in.	20.9	123.4	118.2	2.68	1.864
1	3-in.	28	120.3	118.2	2.68	1.356
2A	2-in.	31.2	121.8	118.2	2.68	1.232
3B	3/4-in.	40	105.4	109.5	2.68	0.898
2	3-in.	46	119.8	118.2	2.68	0.822
3A	2-in.	51	105.7	109.5	2.68	0.706
3	3-in.	52	105.1	109.5	2.68	0.689
4A	2-in.	61.5	104.3	109.5	2.68	0.578
4	3-in.	64	100.5	109.5	2.68	0.535

* Maximum dry unit weight of the minus No.4 fraction determined in the 6-in. diameter mold (see Table 25)

** γ_f of the minus No.4 fraction determined from Equation (1) using the maximum dry unit weight of the total material

Table 55

Corrected Density Interference Coefficients

Based on the Minus 3/4-in. Fraction*

SILT (ML) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1A	2-in.	20.9	131.5	131.6	2.68	1.784
1	3-in.	28	133.3	131.6	2.68	1.350
2A	2-in.	31.2	131.5	131.6	2.68	1.195
2	3-in.	46	129.8	131.6	2.68	0.800
3A	2-in.	51	134.2	134.3	2.68	0.731
3	3-in.	52	133.7	134.6	2.68	0.713
4A	2-in.	61.5	129.3	134.3	2.68	0.584
4	3-in.	64	129.3	134.6	2.68	0.560

CLAY (CH) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1A	2-in.	20.9	126.8	125.6	2.68	1.803
1	3-in.	28	123.8	122.9	2.68	1.342
2A	2-in.	31.2	125.2	125.6	2.68	1.192
2	3-in.	46	123.3	122.9	2.68	0.814
3A	2-in.	51	125.6	126.6	2.68	0.726
3	3-in.	52	123.5	125.0	2.68	0.709
4A	2-in.	61.5	122.9	126.6	2.68	0.589
4	3-in.	64	119.4	125.0	2.68	0.557

* Maximum dry unit weight of the minus 3/4-in. fraction determined in same size mold as the total material (see Table 23)

** γ_f of the minus No.4 fraction determined from Equation (1) using the maximum dry unit weight of the total material

Table 56

Uncorrected Density Interference Coefficients

Based on the Minus 3/4-in. Fraction*

SILT (ML) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1A	2-in.	20.9	131.6	131.8	2.68	1.782
1	3-in.	28	133.3	131.8	2.68	1.348
2A	2-in.	31.2	131.5	131.8	2.68	1.193
2	3-in.	46	129.7	131.8	2.68	0.798
3A	2-in.	51	134.2	134.3	2.68	0.731
3	3-in.	52	133.8	134.3	2.68	0.715
4A	2-in.	61.5	129.3	134.3	2.68	0.584
4	3-in.	64	129.2	134.3	2.68	0.561

CLAY (CH) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f** -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
1A	2-in.	20.9	126.8	123.4	2.68	1.835
1	3-in.	28	123.8	123.4	2.68	1.337
2A	2-in.	31.2	125.2	123.4	2.68	1.213
2	3-in.	46	123.4	123.4	2.68	0.811
3A	2-in.	51	125.6	123.7	2.68	0.743
3	3-in.	52	123.4	123.7	2.68	0.716
4A	2-in.	61.5	122.9	123.7	2.68	0.603
4	3-in.	64	119.4	123.7	2.68	0.563

* Maximum dry unit weight of the minus 3/4-in. fraction determined in the 6-in. diameter mold (see Table 23)

** γ_f of the minus No.4 fraction determined from Equation (1) using the maximum dry unit weight of the total material

Table 57

Uncorrected Density Interference Coefficients

Based on the Minus No.4 Fraction

Data From Garga and Madureira (1985)

TEST SERIES NO.*	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
			STANDARD EFFORT			
1	3/4-in.	30	116.6	119.8	2.59	1.253
1		40	113.9	119.8	2.59	0.918
1		50	109.4	119.8	2.59	0.705
1		60	103.9	119.8	2.59	0.558
1		70	91.9	119.8	2.59	0.423
2	1-1/2-in.	30	113.6	117.3	2.59	1.247
2		40	112.2	117.3	2.59	0.923
2		50	109.4	117.3	2.59	0.720
2		60	103.9	117.3	2.59	0.570
			INTERMEDIATE EFFORT			
3	3/4-in.	30	121.2	119.8	2.59	1.302
3		40	117.2	119.8	2.59	0.944
3		50	112.8	119.8	2.59	0.727
3		60	106.9	119.8	2.59	0.574
4	3/4-in.	30	120.4	124.8	2.59	1.242
4		40	117.1	124.8	2.59	0.906
4		50	114.7	124.8	2.59	0.710
4		60	110.9	124.8	2.59	0.572
4		65	107.2	124.8	2.59	0.510
4		70	100.5	124.8	2.59	0.444
5	1-1/2-in.	30	121.2	121.7	2.59	1.282
5		40	120.5	121.7	2.59	0.956
5		50	115.7	121.7	2.59	0.734
5		60	111.0	121.7	2.59	0.587
6	1-1/2-in.	30	119.6	122.3	2.59	1.259
6		40	118.8	122.3	2.59	0.938
6		50	112.9	122.3	2.59	0.713
6		60	109.8	122.3	2.59	0.578
6		70	102.7	122.3	2.59	0.463
7	3-in.	30	118.1	126.0	2.59	1.206
7		40	118.4	126.0	2.59	0.907
7		50	117.5	126.0	2.59	0.720
7		60	112.6	126.0	2.59	0.575

(Continued)

Table 57 (Concluded)

TEST SERIES NO.*	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	γ_f -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
7	3-in.	70	105.3	126.0	2.59	0.461
8	3-in.	30	119.6	122.9	2.59	1.253
8		40	117.1	122.9	2.59	0.920
8		50	113.8	122.9	2.59	0.715
8		60	111.9	122.9	2.59	0.586
8		70	104.9	122.9	2.59	0.471
		MODIFIED EFFORT				
9	3/4-in.	30	123.5	126.7	2.59	1.255
9		40	122.2	126.7	2.59	0.931
9		70	101.8	126.7	2.59	0.443
10	1-1/2-in.	30	123.4	131.0	2.56	1.227
10		40	119.6	131.0	2.56	0.892
10		50	117.4	131.0	2.56	0.700
10		60	109.9	131.0	2.56	0.546
10		65	107.2	131.0	2.56	0.492
10		70	101.4	131.0	2.56	0.432
11	1-1/2-in.	30	119.7	124.2	2.59	1.240
11		50	116.4	124.2	2.59	0.724
11		65	107.3	124.2	2.59	0.513
12	3-in.	40	119.5	128.5	2.59	0.898
12		50	115.5	128.5	2.59	0.694
12		60	114.0	128.5	2.59	0.571
12		65	111.6	128.5	2.59	0.516
12		70	105.1	128.5	2.59	0.451

* The minus No.4 material was different for each test series with respect to Atterberg limits, specific gravity of solids and percent finer than the No. 200 sieve

Table 58

Density Interference Coefficients Based on the Minus No.4 Fraction

Data from Donaghe and Townsend (1975) and USBR (1963)

	Percent Gravel P_g	γ_f -NO.4 pcf	γ_{fmax} pcf	G_m	INTERFERENCE COEFFICIENT I_c
DONAGHE AND TOWNSEND, MINUS 3-IN. UNCORRECTED DATA, (see Table 6)					
	10	132.6	132.0	2.58	3.894
	20	131.0	131.0	2.58	1.938
	30	129.0	128.5	2.58	1.297
	40	125.9	127.0	2.58	0.961
	50	119.3	124.8	2.58	0.741
	60	108.6	119.3	2.58	0.588
DONAGHE AND TOWNSEND, MINUS 3/4-IN. SCALPED/REPLACED UNCORRECTED DATA, (see Table 6)					
	10	131.0	132.0	2.58	3.847
	20	126.9	131.0	2.58	1.877
	30	122.9	128.5	2.58	1.236
	40	116.6	127.0	2.58	0.890
	50	111.7	124.8	2.58	0.694
	60	100.1	119.3	2.58	0.542
DONAGHE AND TOWNSEND, MINUS 3-IN., VARIABLE FINES UNCORRECTED DATA, (see Table 6)					
PERCENT FINES = 15.0	40	131.4	132.1	2.58	0.964
PERCENT FINES = 25.0	40	126.0	127.0	2.58	0.961
PERCENT FINES = 35.0	40	119.6	121.5	2.58	0.954
DONAGHE AND TOWNSEND, MINUS 3/4-IN. SCALPED/REPLACED VARIABLE FINES, UNCORRECTED DATA, (see Table 6)					
PERCENT FINES = 15.0	40	121.6	132.1	2.58	0.892
PERCENT FINES = 25.0	40	116.6	127.0	2.58	0.890
PERCENT FINES = 35.0	40	110.7	121.5	2.58	0.883
USBR, CORRECTED DATA					
MINUS 3/8-IN.	16.7	130.4	133.1	2.62	2 2.0
MINUS 3/4-IN.	28.6	128.4	133.1	2.62	1.288
MINUS 1-1/2-IN.	41.2	125.3	133.1	2.62	0.872
MINUS 3-IN.	50	122.6	133.1	2.62	0.703
USBR, UNCORRECTED DATA					
MINUS 3/8-IN.	16.7	130.4	124.0	2.62	2.404
MINUS 3/4-IN.	28.6	128.5	124.0	2.62	1.383
MINUS 1-1/2-IN.	41.2	125.8	124.0	2.62	0.940
MINUS 3-IN.	50	123.0	124.0	2.62	0.757

Table 59

Uncorrected Density Interference Coefficients

Based on the Minus No.4 Fraction

Data From Gordon, Hammond and Miller (1964)

TEST NO.*	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_s	γ_f -NO.4 pcf	γ_{fmax} pcf	G_m**	INTERFERENCE COEFFICIENT I_c
1-4043	3/4-in.	35	121.5	126.6	2.79	0.983
	1-1/2-in.	50	116.7	126.6	2.79	0.661
	4-in.	62	112.3	126.6	2.80	0.511
1-4044	3/4-in.	24	120.5	124.3	2.79	1.448
	1-1/2-in.	34	119.1	124.3	2.79	1.010
	4-in.	43	113.7	124.3	2.80	0.760
1-4045	3/4-in.	18	121.1	122.0	2.79	1.976
	1-1/2-in.	26	120.5	122.0	2.79	1.362
	4-in.	35	116.2	122.0	2.80	0.972
1-4046	3/4-in.	21	125.0	123.0	2.79	1.735
	1-1/2-in.	32	121.3	123.0	2.79	1.105
	4-in.	42	112.5	123.0	2.80	0.778
1-4047	3/4-in.	25	117.7	118.7	2.79	1.422
	1-1/2-in.	38	116.2	118.7	2.79	0.923
	4-in.	50	109.0	118.7	2.80	0.656
1-4047A	3/4-in.	25	118.4	119.4	2.79	1.422
	1-1/2-n.	38	117.0	119.4	2.79	0.924
	4-in.	50	107.1	119.4	2.80	0.641
1-4048	3/4-in.	30	123.1	128.0	2.79	1.149
	1-1/2-in.	44	121.0	128.0	2.79	0.770
	4-in.	58	111.4	128.0	2.80	0.536

* See Table 1 for basic test data

** Bulk specific gravities of gravel fractions were variable (see Table 2) A weighted value was calculated based on approximate percentage of each fraction contained in each material grading group (see Table 2 and Figure 8)

Table 60

Uncorrected Optimum Water Content Factor

Based on the Minus No.4 Fraction

SILT (ML) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	w_{optf}* percent	w_{optt}** percent	OPTIMUM WATER CONTENT FACTOR F_{opt}
1B	3/4-in.	10	7.7	7.6	10.132
1A	2-in.	20.9	7.7	5.9	6.244
1	3-in.	28	7.7	5.6	4.911
2A	2-in.	31.2	7.7	5.3	4.656
3B	3/4-n.	40	10.6	7.5	3.533
2	3-in.	46	7.7	4.9	3.416
3A	2-in.	51	10.6	6.3	3.299
3	3-in.	52	10.6	5.6	3.640
4A	2-in.	61.5	10.6	5.6	3.078
4	3-in.	64	10.6	5.4	3.067

CLAY (CH) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	w_{optf}* percent	w_{optt}** percent	OPTIMUM WATER CONTENT FACTOR F_{opt}
1B	3/4-in.	10	12.7	10.5	12.095
1A	2-in.	20.9	12.7	8.4	7.234
1	3-in.	28	12.7	8.4	5.400
2A	2-in.	31.2	12.7	8.0	5.088
3B	3/4-in.	40	15.2	9.8	3.878
2	3-in.	46	12.7	6.9	4.001
3A	2-in.	51	15.2	8.2	3.635
3	3-in.	52	15.2	7.3	4.004
4A	2-in.	61.5	15.2	7.4	3.340
4	3-in.	64	15.2	6.8	3.493

* Optimum water content of the minus No.4 fraction determined in the 6-in. diameter mold. (see Table 36)

** Optimum water content of the total material (see Table 36)

Table 61

Uncorrected Optimum Water Content Factor

Based on the Minus 3/4-in. Fraction

SILT (ML) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	w_{optf}* percent	w_{optt}** percent	OPTIMUM WATER CONTENT FACTOR F_{opt}
1A	2-in.	20.9	7.6	5.9	6.163
1	3-in.	28	7.6	5.6	4.847
2A	2-in.	31.2	7.6	5.3	4.596
2	3-in.	46	7.6	4.9	3.372
3A	2-in.	51	7.5	6.3	2.334
3	3-in.	52	7.5	5.6	2.576
4A	2-in.	61.5	7.5	5.6	2.178
4	3-in.	64	7.5	5.4	2.170

CLAY (CH) FINES

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	w_{optf}* percent	w_{optt}** percent	OPTIMUM WATER CONTENT FACTOR F_{opt}
1A	2-in.	20.9	10.5	8.4	5.981
1	3-in.	28	10.5	8.4	4.464
2A	2-in.	31.2	10.5	8.0	4.207
2	3-in.	46	10.5	6.9	3.308
3A	2-in.	51	9.8	8.2	2.343
3	3-in.	52	9.8	7.3	2.582
4A	2-in.	61.5	9.8	7.4	2.153
4	3-in.	64	9.8	6.8	2.252

* Optimum water content of the minus 3/4-in. fraction determined in the 6-in. diameter mold. (see Table 36)

** Optimum water content of the total material (see Table 36)

Table 62

Uncorrected Optimum Water Content* Factor

Based on the Minus No. 4 Fraction

Data From USBR (1963), Donaghe and Townsend (1975) and

Garga and Madureira (1985)

	Percent Gravel P_g	w_{optf}** percent	w_{optt}*** percent	OPTIMUM WATER CONTENT FACTOR F_{opt}
DONAGHE AND TOWNSEND, MINUS 3-IN.				
	10	8.2	6.7	12.239
	20	8.6	6.1	7.049
	30	9.3	5.7	5.439
	40	9.8	5.9	4.152
	50	10.5	5.8	3.621
	60	11.9	5.2	3.814
USBR, UNCORRECTED DATA				
MINUS 3/8-IN.	16.7	10.5	7.8	8.061
MINUS 3/4-IN.	28.6	10.5	7.1	5.171
MINUS 1-1/2-IN.	41.2	10.5	6.5	3.921
MINUS 3-IN.	50	10.5	6.2	3.387
GARGA AND MADUREIRA, MINUS 1-1/2-IN.				
	30	14.6	10.7	4.548
	40	14.6	9.7	3.763
	50	14.6	8.4	3.476
	60	14.6	7.3	3.333

* Standard Effort

** Optimum water content of the minus No.4 fraction determined in 4-in. diameter mold

*** Optimum water content of the total material

Table 63

Uncorrected Optimum Water Content* Factor

Based on the Minus No. 4 Fraction

Data From Gordon, Hammond and Miller (1964)

GRADATION NO.	MAXIMUM PARTICLE SIZE, IN.	Percent Gravel P_g	w_{optf}** percent	w_{optt}*** percent	OPTIMUM WATER CONTENT FACTOR F_{opt}
1-4043	3/4-in.	35	12.2	9.1	3.830
	1-1/2-in.	50	12.2	7.7	3.169
	4-in.	62	12.2	7.7	2.556
1-4044	3/4-in.	24	13.0	11.3	4.794
	1-1/2-in.	34	13.0	9.9	3.862
	4-in.	43	13.0	9.5	3.182
1-4045	3/4-in.	18	13.3	11.7	6.315
	1-1/2-in.	26	13.3	10.6	4.826
	4-in.	35	13.3	8.3	4.578
1-4046	3/4-in.	21	13.2	11.1	5.663
	1-1/2-in.	32	13.2	9.6	4.297
	4-in.	42	13.2	9.8	3.207
1-4047	3/4-in.	25	15.0	12.0	5.000
	1-1/2-in.	38	15.0	10.1	3.908
	4-in.	50	15.0	9.6	3.125
1-4047A	3/4-in.	25	14.6	11.3	5.168
	1-1/2-n.	38	14.6	9.8	3.920
	4-in.	50	14.6	9.9	2.949
1-4048	3/4-in.	30	11.5	9.0	4.259
	1-1/2-in.	44	11.5	7.9	3.308
	4-in.	58	11.5	8.0	2.478

* Standard Effort

** Optimum water content of the minus No.4 fraction determined in 4-in. diameter mold

*** Optimum water content of the total material

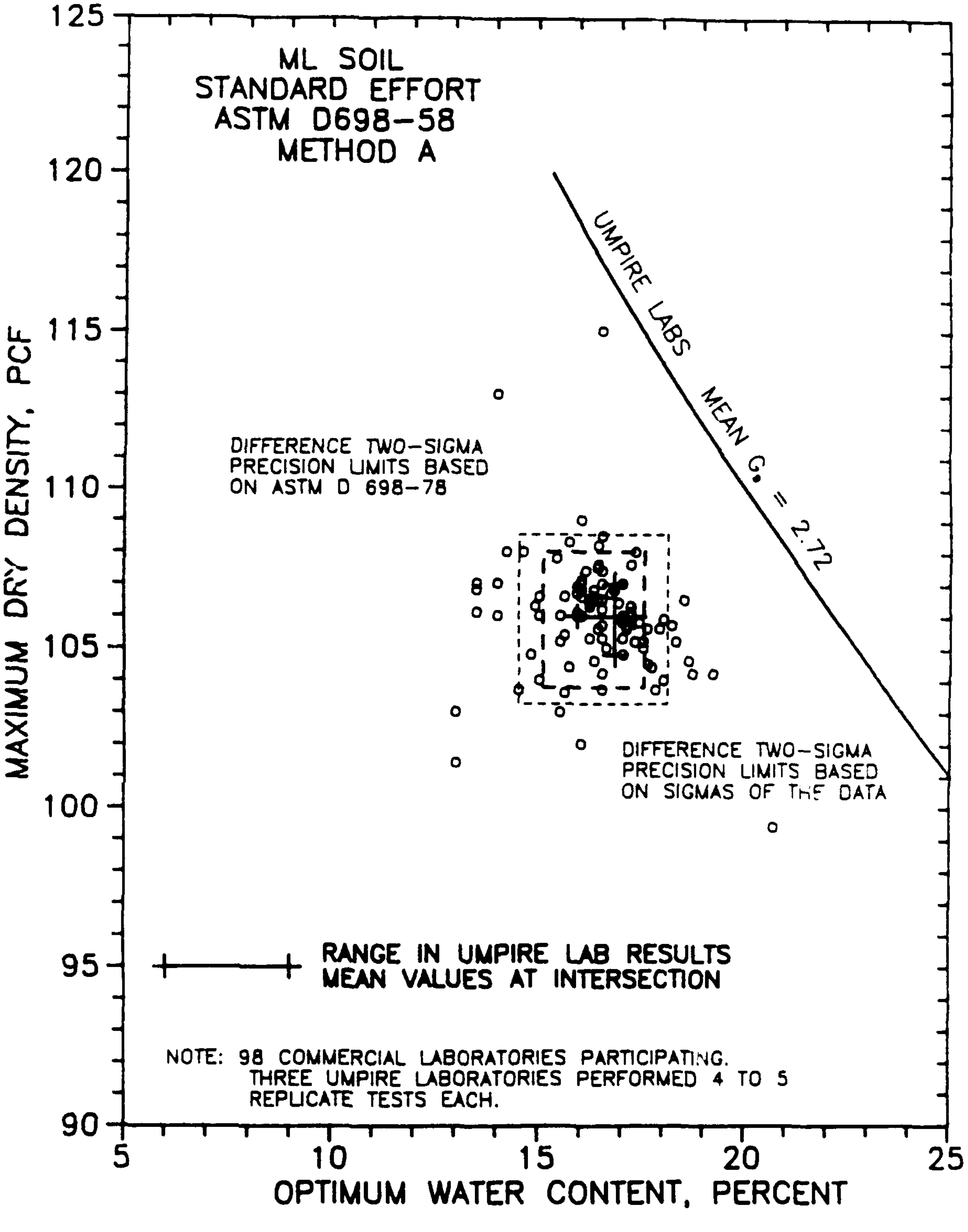


Figure 1. 1964 ACIL study, results of standard effort compaction tests by commercial and umpire laboratories on "standard" ML soil.

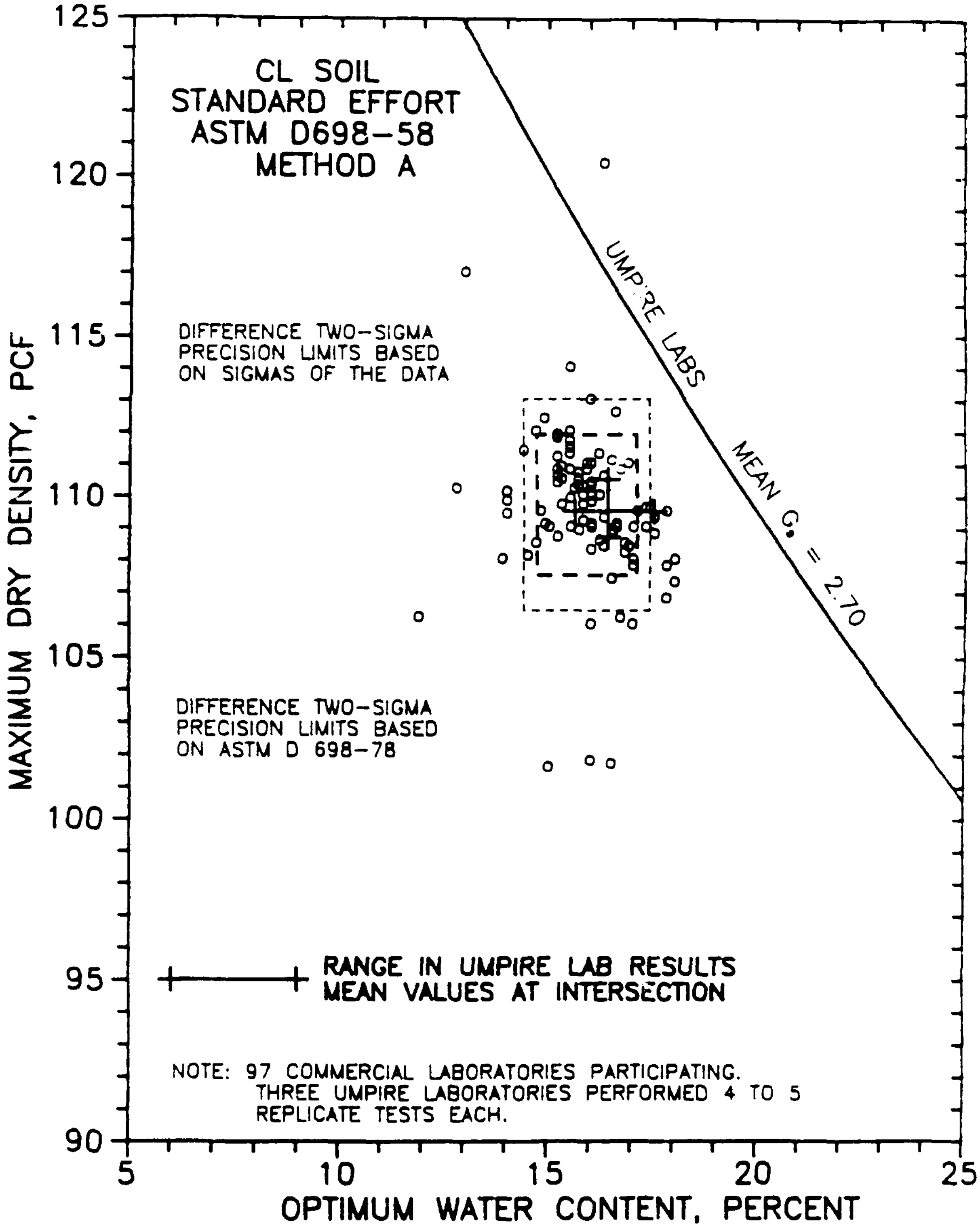


Figure 2. 1964 ACIL study, results of standard effort compaction tests by commercial and umpire laboratories on "standard" CL soil.

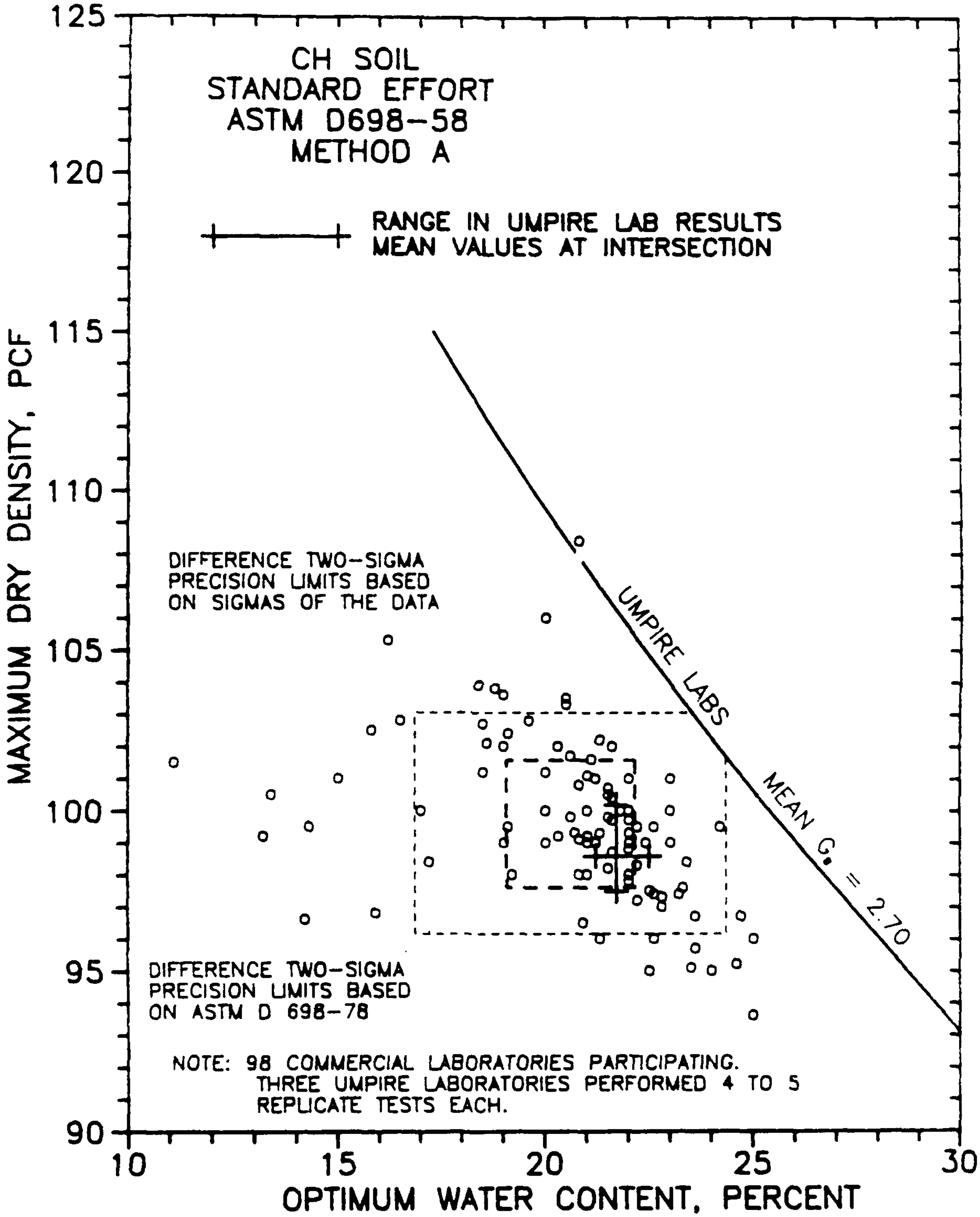


Figure 3. 1964 ACIL study, results of standard effort compaction tests by commercial and umpire laboratories on "standard" CH soil.

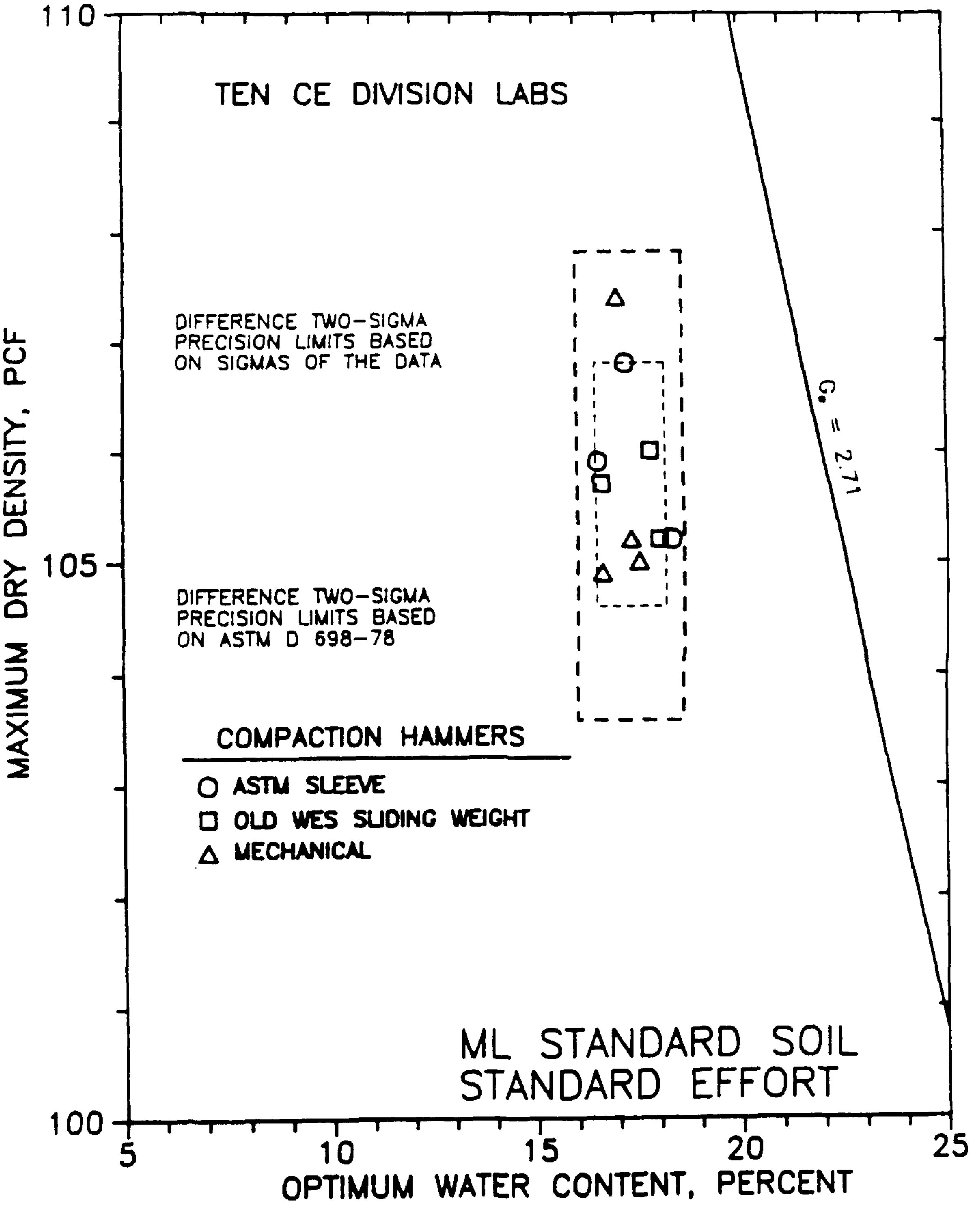


Figure 4. Results of standard effort compaction tests by ten CE Division laboratories on the ACIL "standard" silt (ML) soil

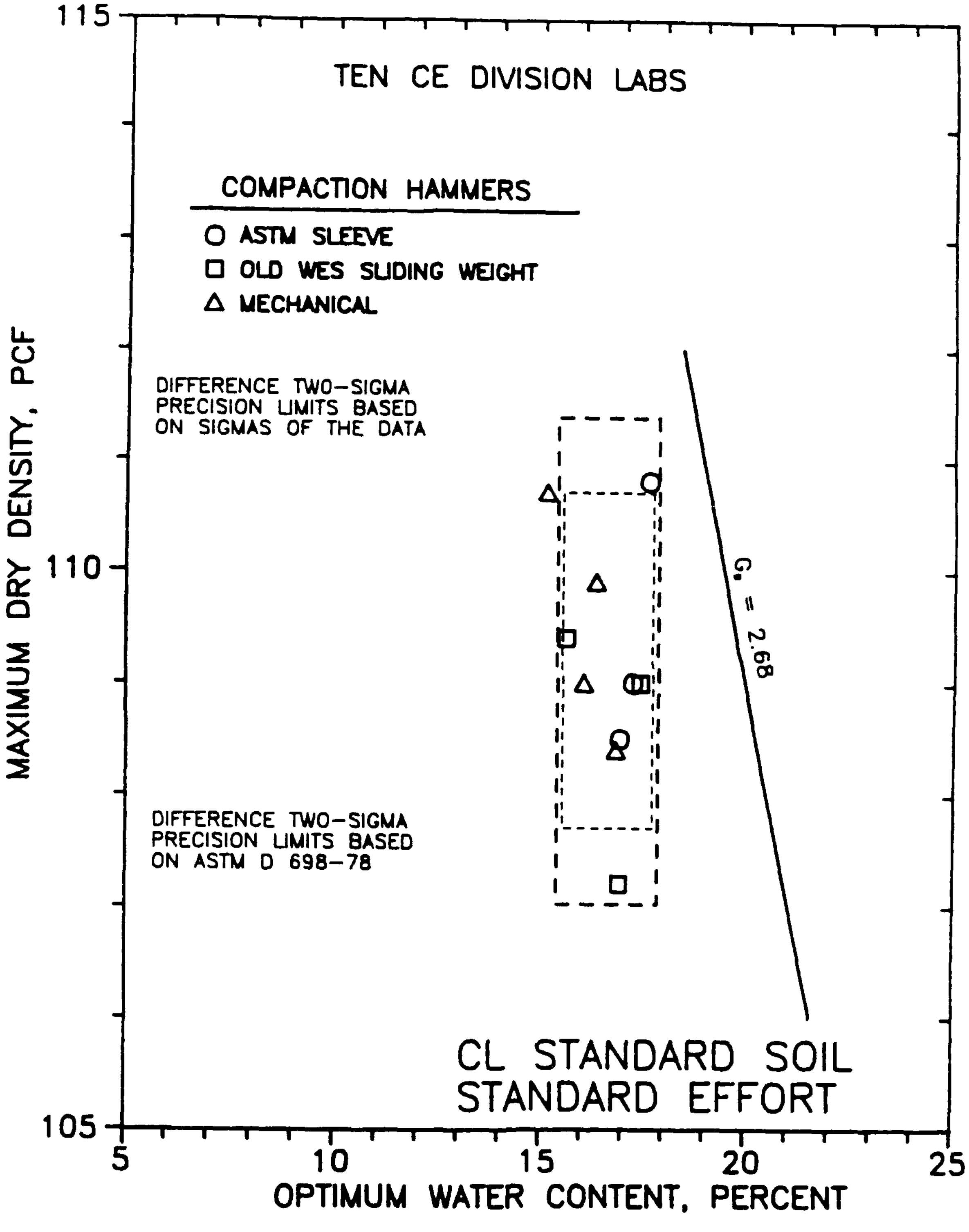


Figure 5. Results of standard effort compaction tests by ten CE Division laboratories on the ACIL "standard" clay (CL) soil

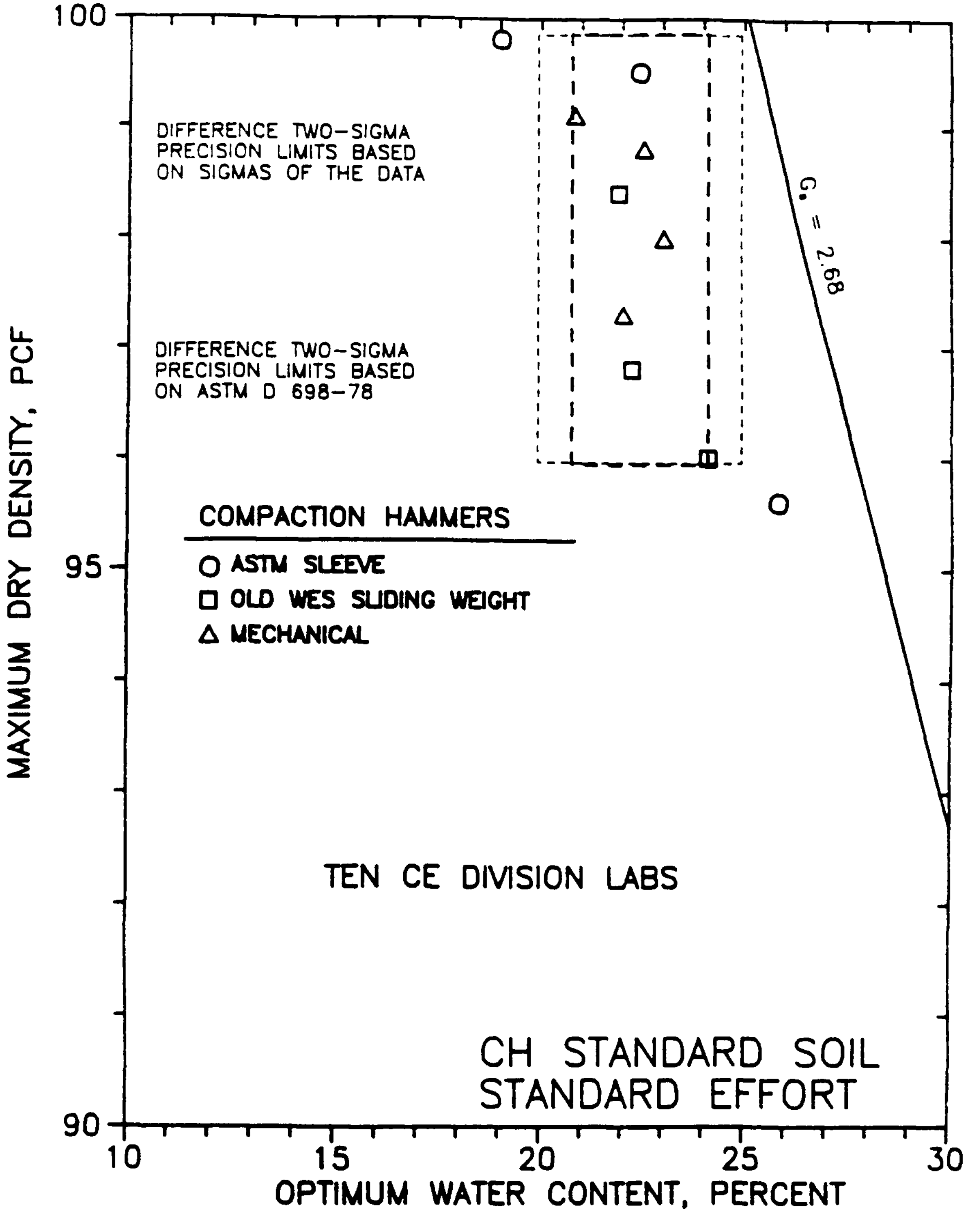


Figure 6. Results of standard effort compaction tests by ten CE Division laboratories on the ACIL "standard" clay (CH) soil

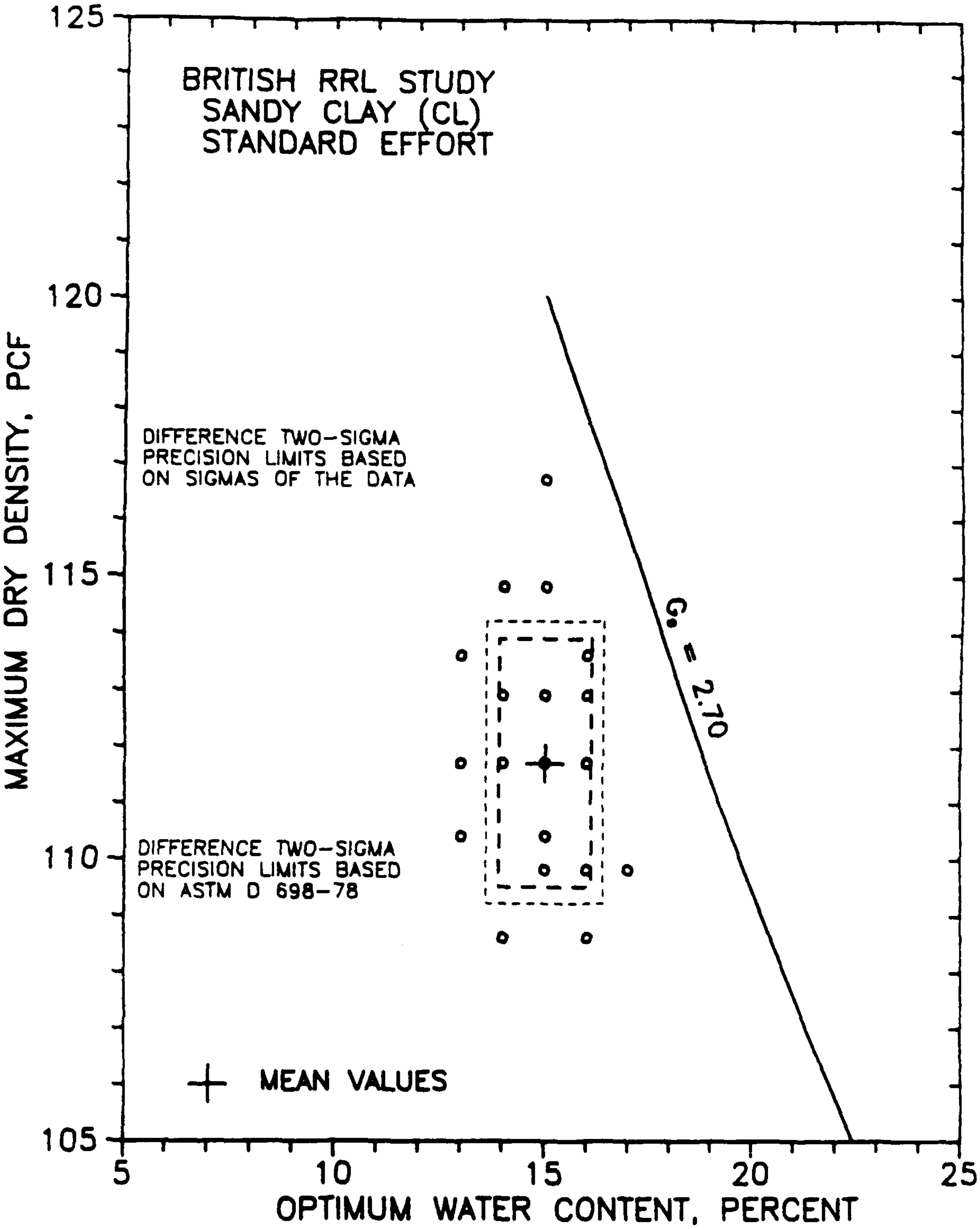


Figure 7. 1970 British RRL study, results of standard effort compaction tests by various government, university and private laboratories on a sandy clay (CL)

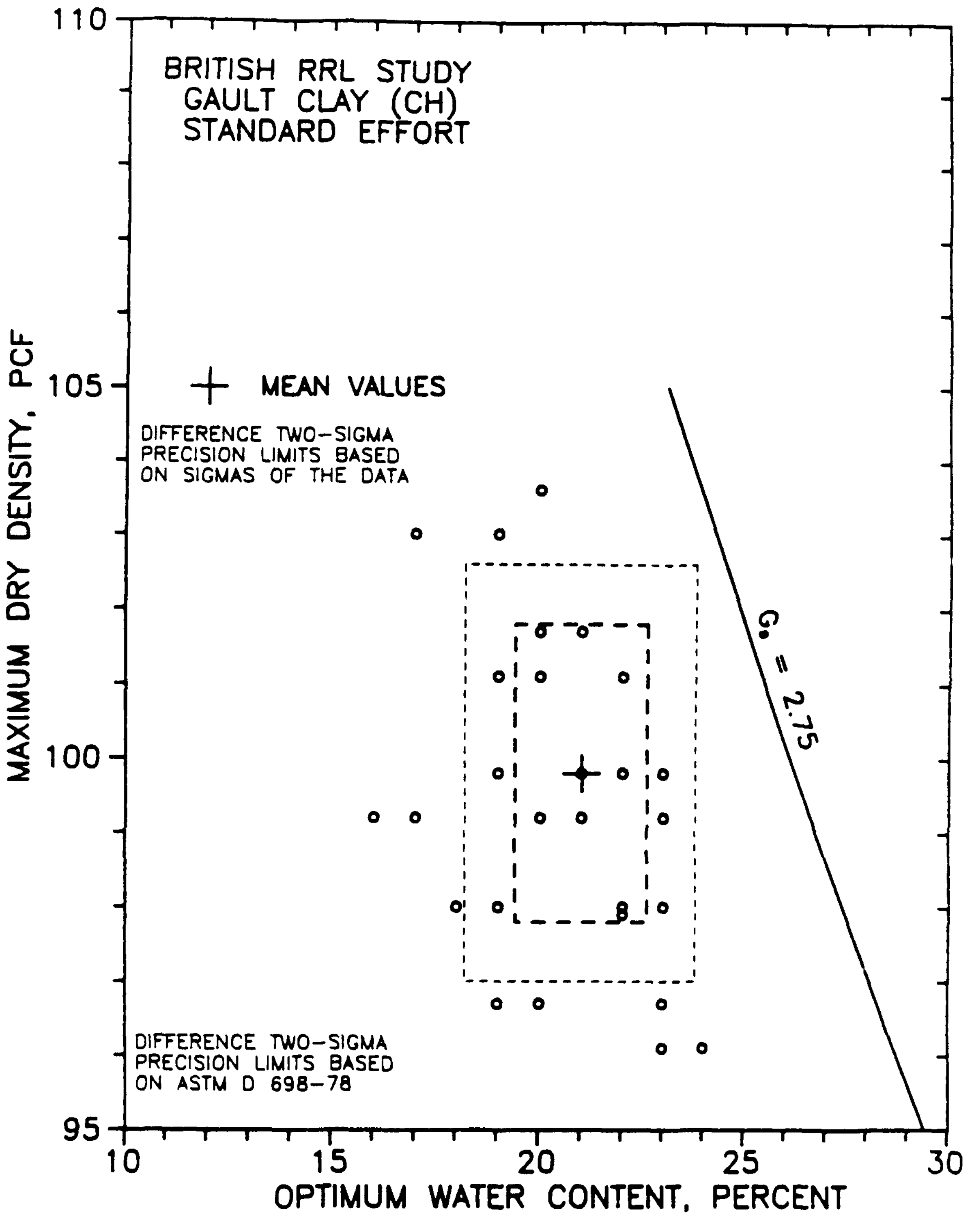


Figure 8. 1970 British RRL study, results of standard effort compaction tests by various government, university and private laboratories on Gault clay (CH)

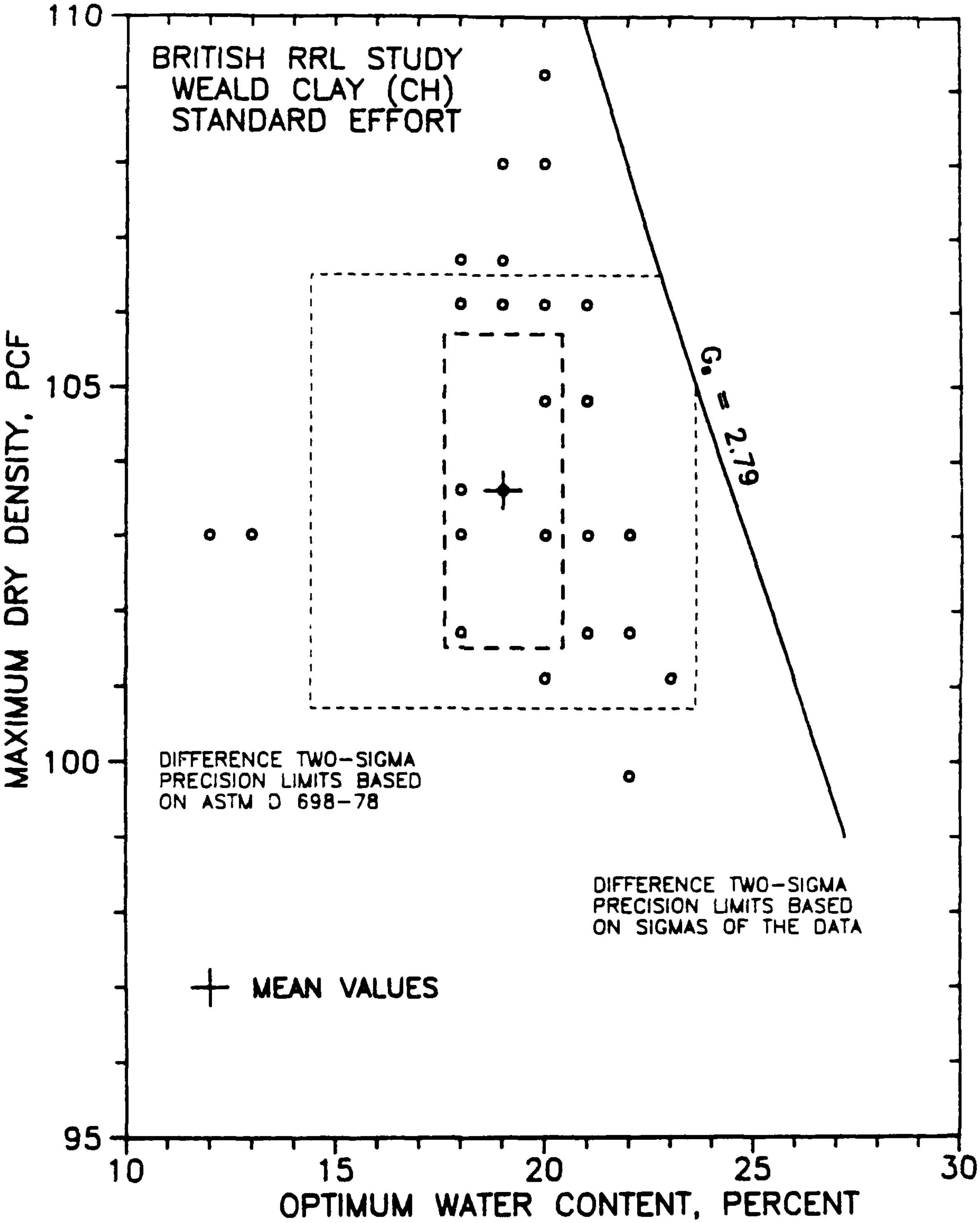


Figure 9. 1970 British RRL study, results of standard effort compaction tests by various government, university and private laboratories on Weald clay (CH)

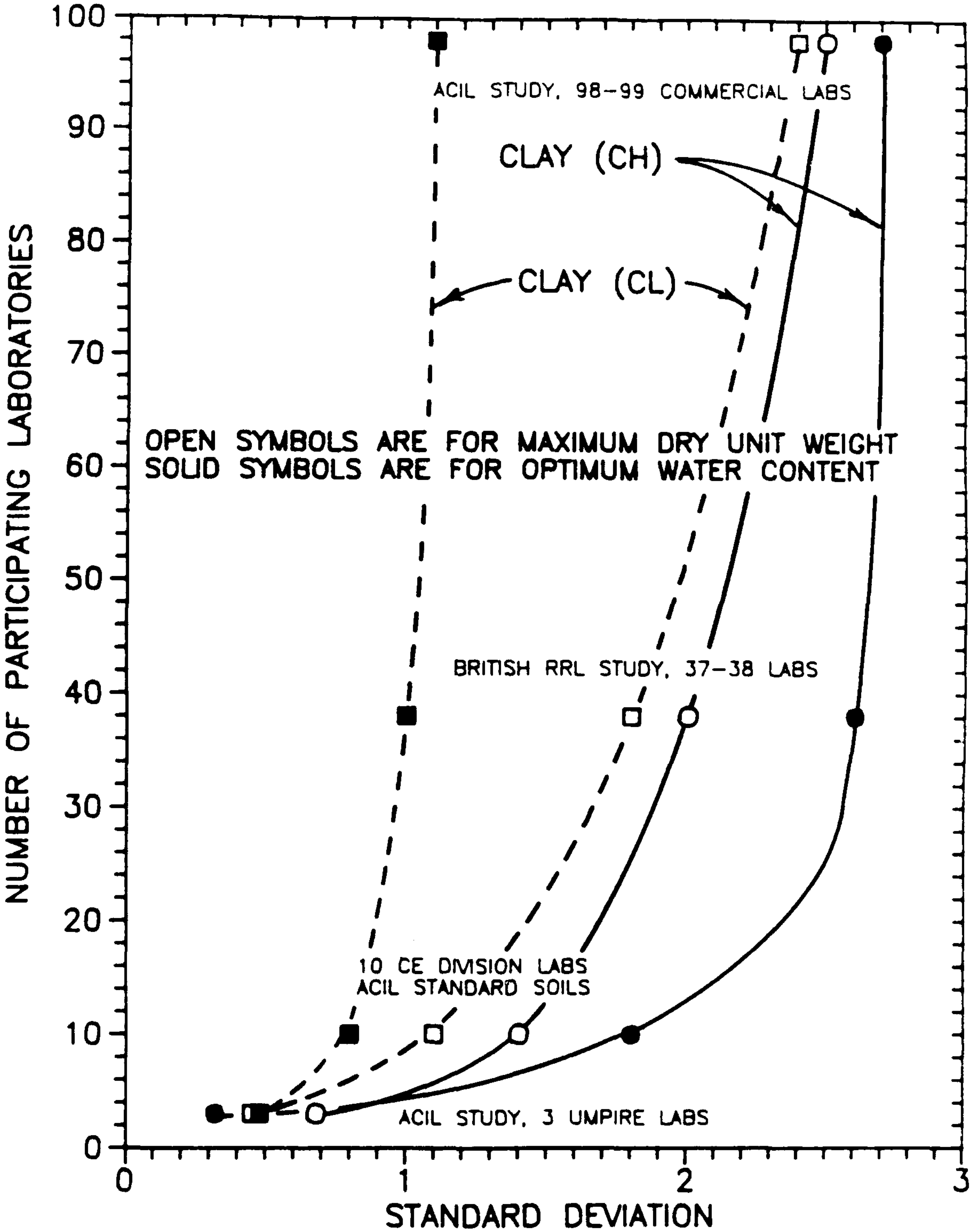
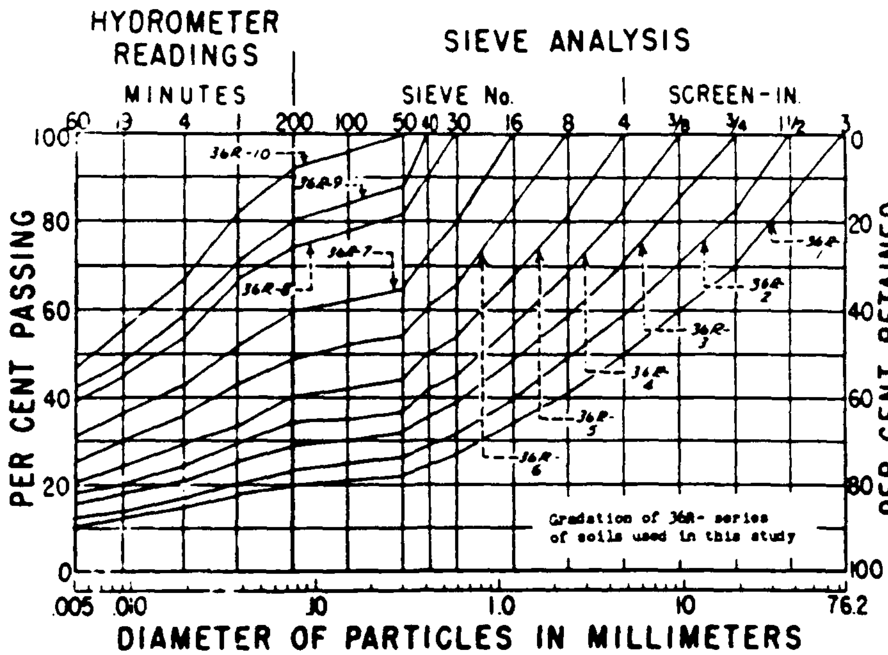
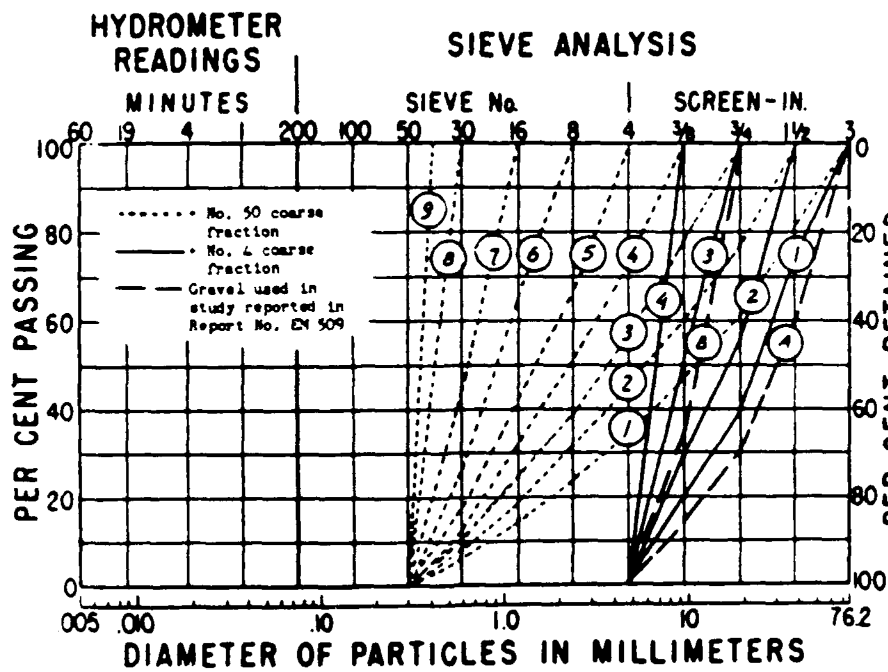


Figure 10. Variations in standard deviations of multi-laboratory standard effort compaction parameters for clay soils of the ACIL and British RRL studies with number of participating laboratories

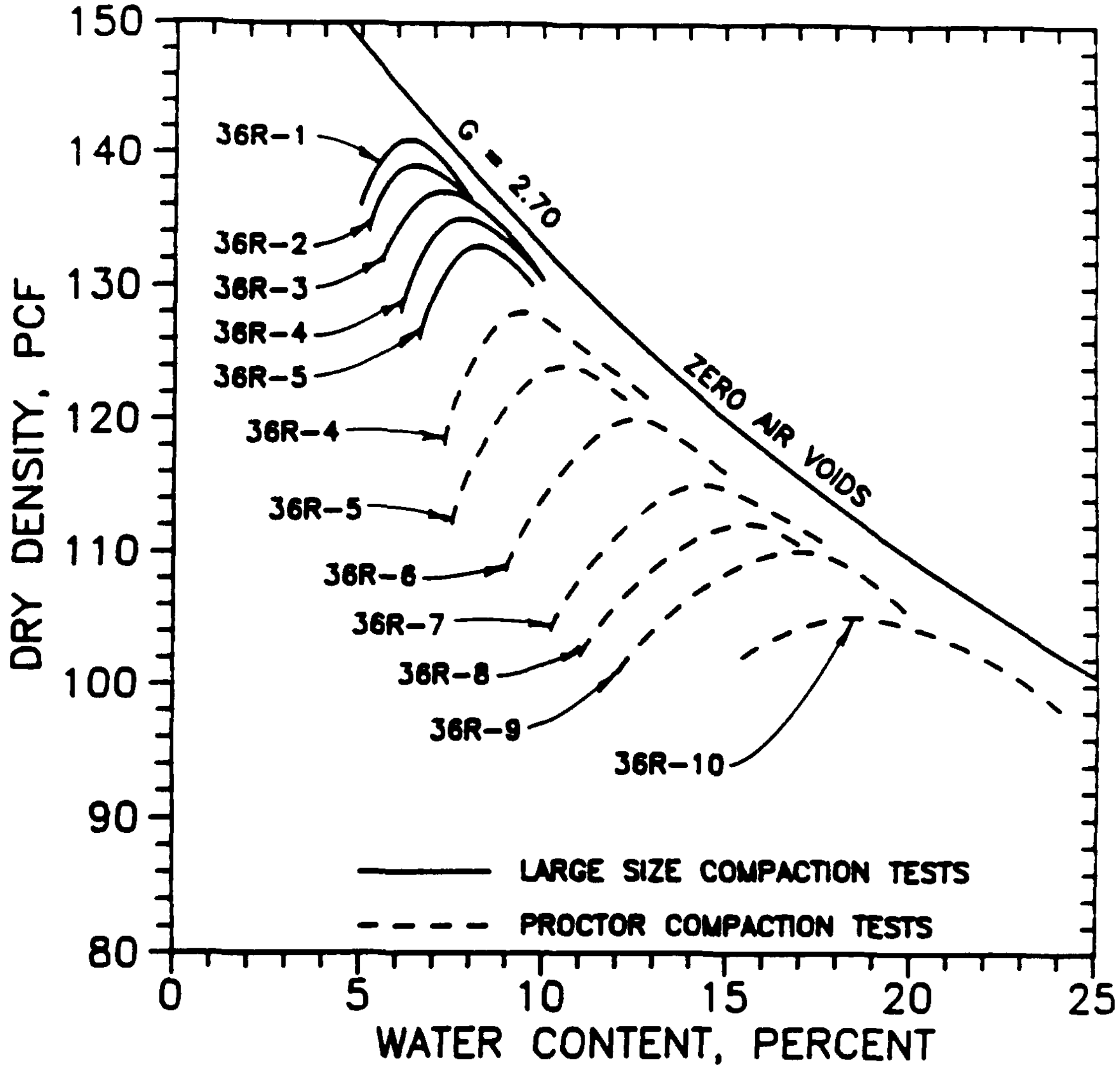


A



B

Figure 11. Grain-size distribution curves for materials employed in the testing program (After USBR, 1963)



SAMPLE NO.	MAXIMUM PARTICLE SIZE	TYPE COMPACTION	PERCENT COARSE PARTICLES +NO.4	+NO.50	MAXIMUM DRY DENSITY PCF	OPTIMUM WATER CONTENT PERCENT
36R-1	3"	Large Size	50	78	141	6.2
36R-2	1.5"	"	41	74	139	6.3
36R-3	3/4"	"	29	68	137	7.0
36R-4	3/8"	"	17	63	135	7.6
36R-5	#4	"	0	55	133	8.2
36R-4	3/8"	Std. Proctor	17	63	128	9.4
36R-5	#4	"	0	55	124	10.7
36R-6	#8	"	0	46	120	12.6
36R-7	#16	"	0	35	115	14.4
36R-8	#30	"	0	18	112	15.8
36R-9	#40	"	0	12	110	17.1
36R-10	#50	"	0	0	105	18.2

Figure 12. Compaction curves for tests performed to determine effects of large particles (After USBR, 1963)

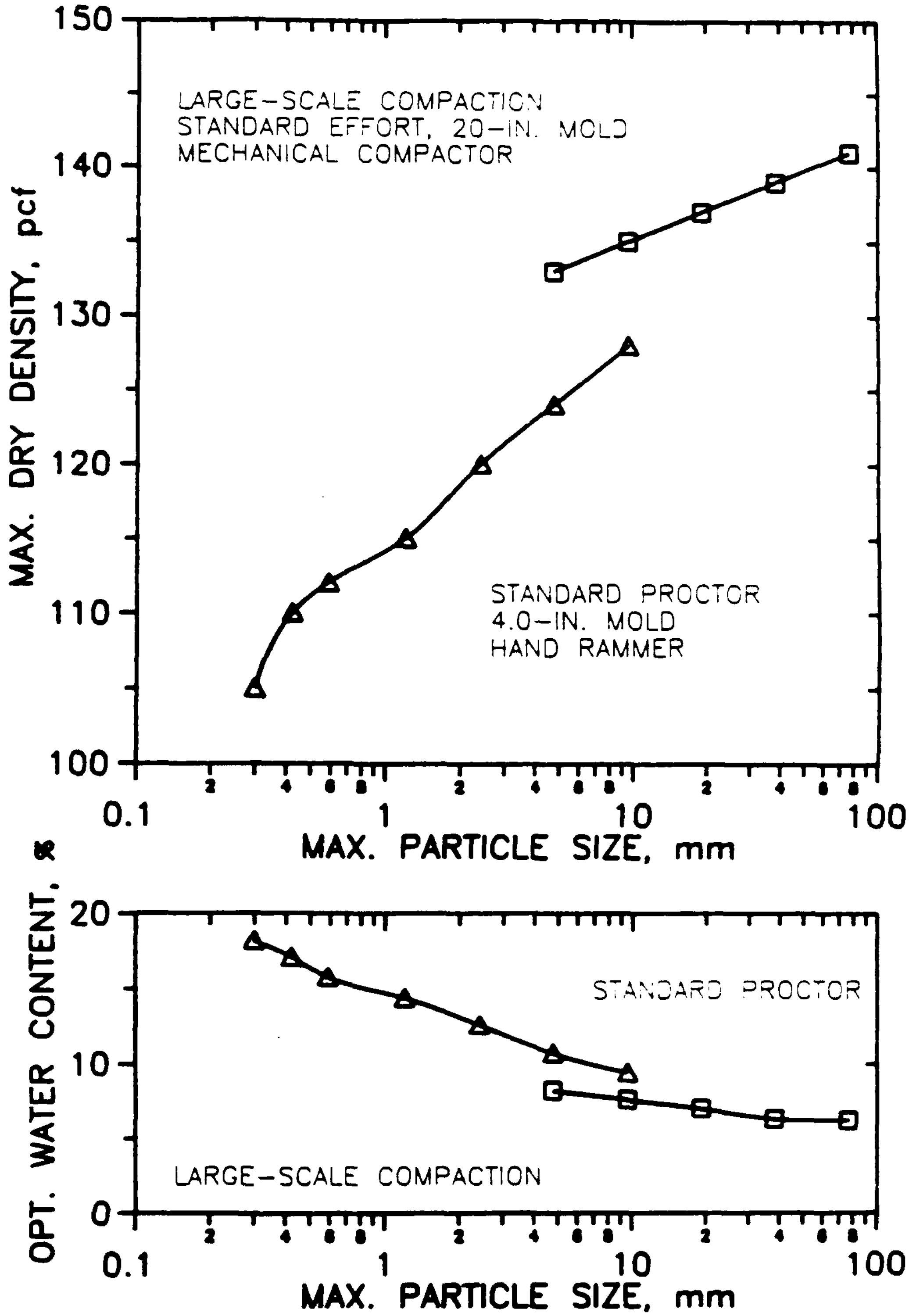


Figure 13. Maximum dry density and optimum water content versus maximum particle size (After USBR, 1963)

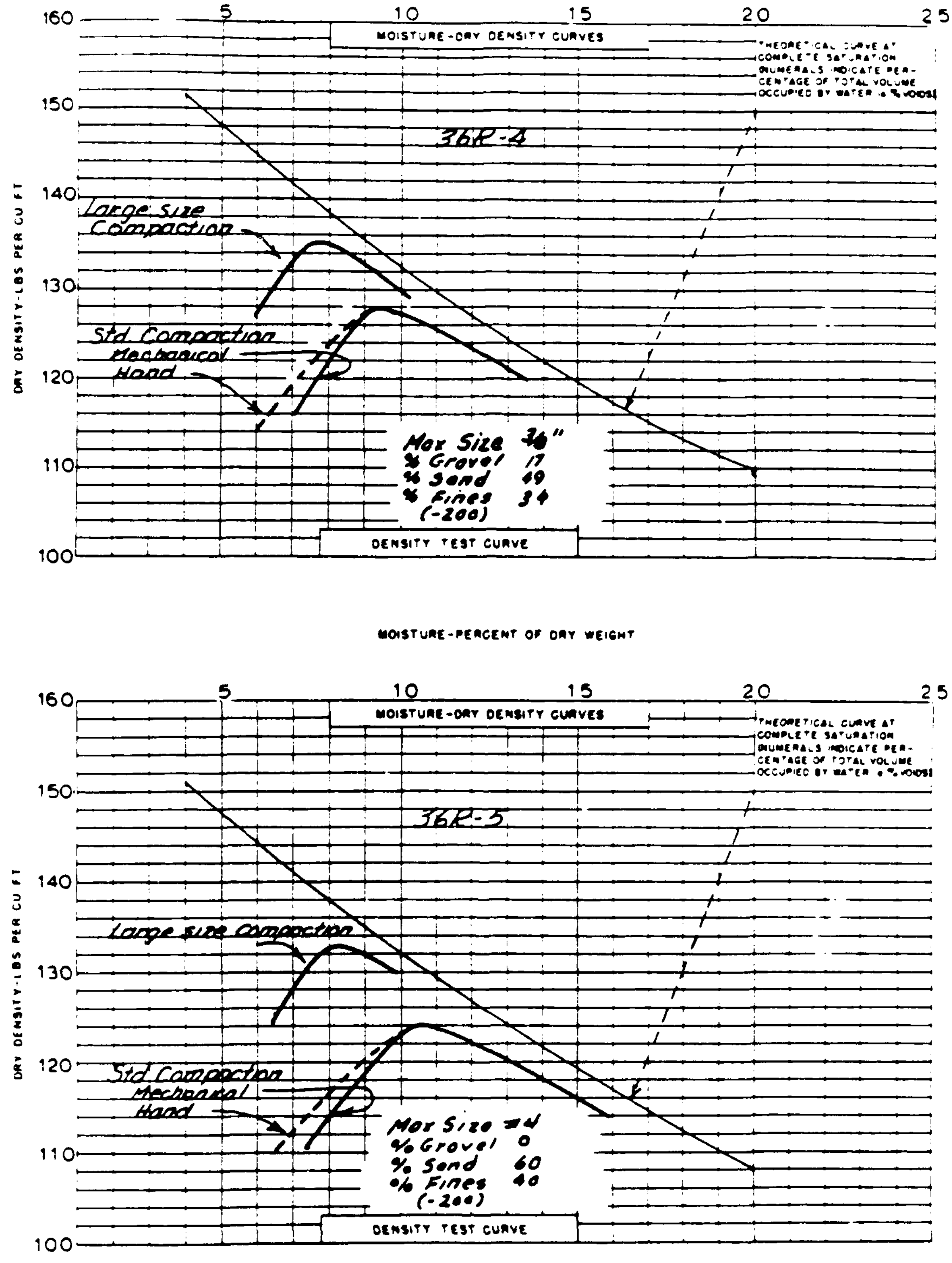


Figure 14. Compaction curves for tests performed to determine effects of different mold sizes and hand-held rammer versus mechanical compactor (After USBR, 1963)

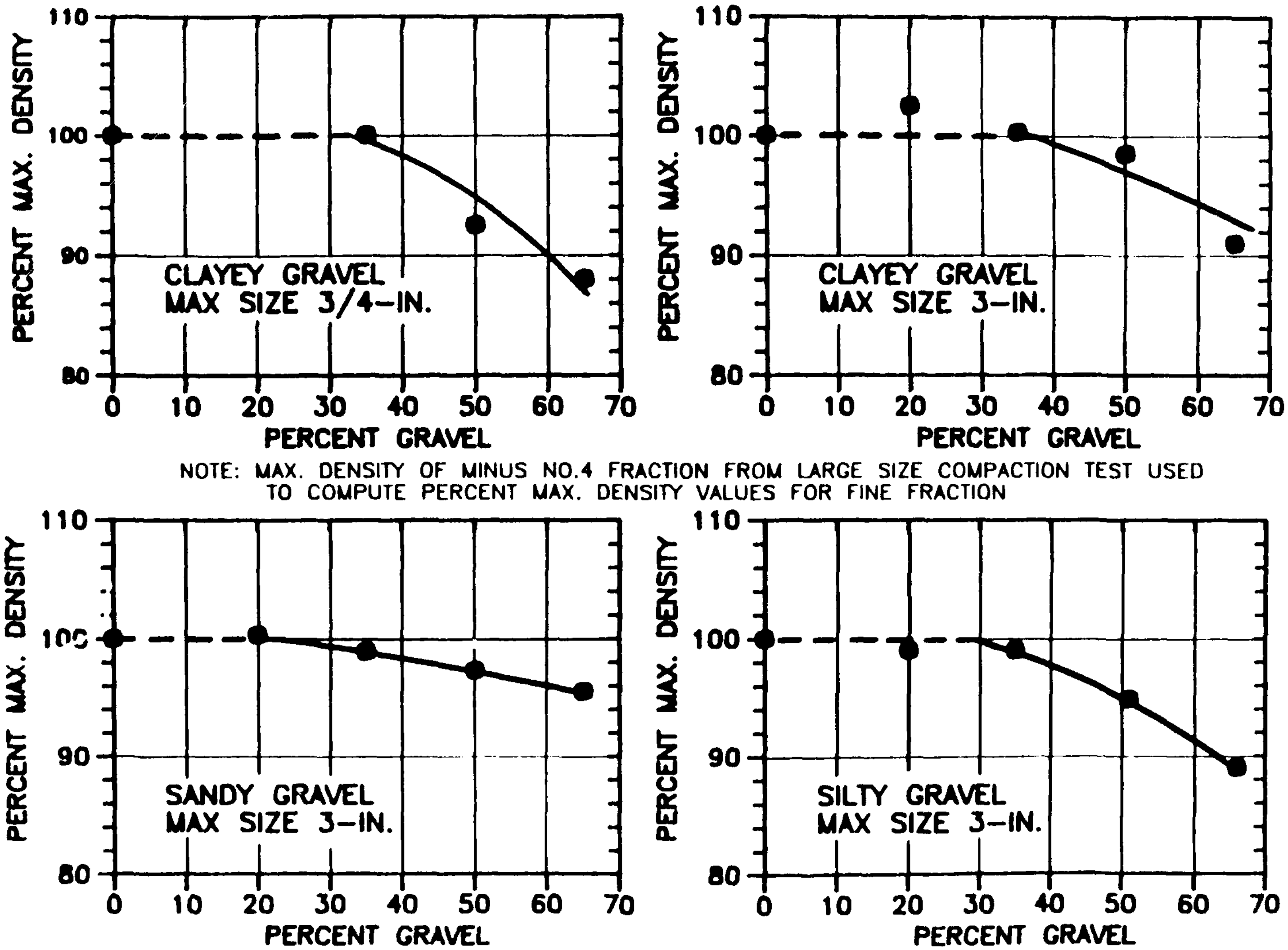


Figure 15. Data obtained from EM-509 showing how the density of the fine fraction varied with increased gravel content (After USBR, 1963)

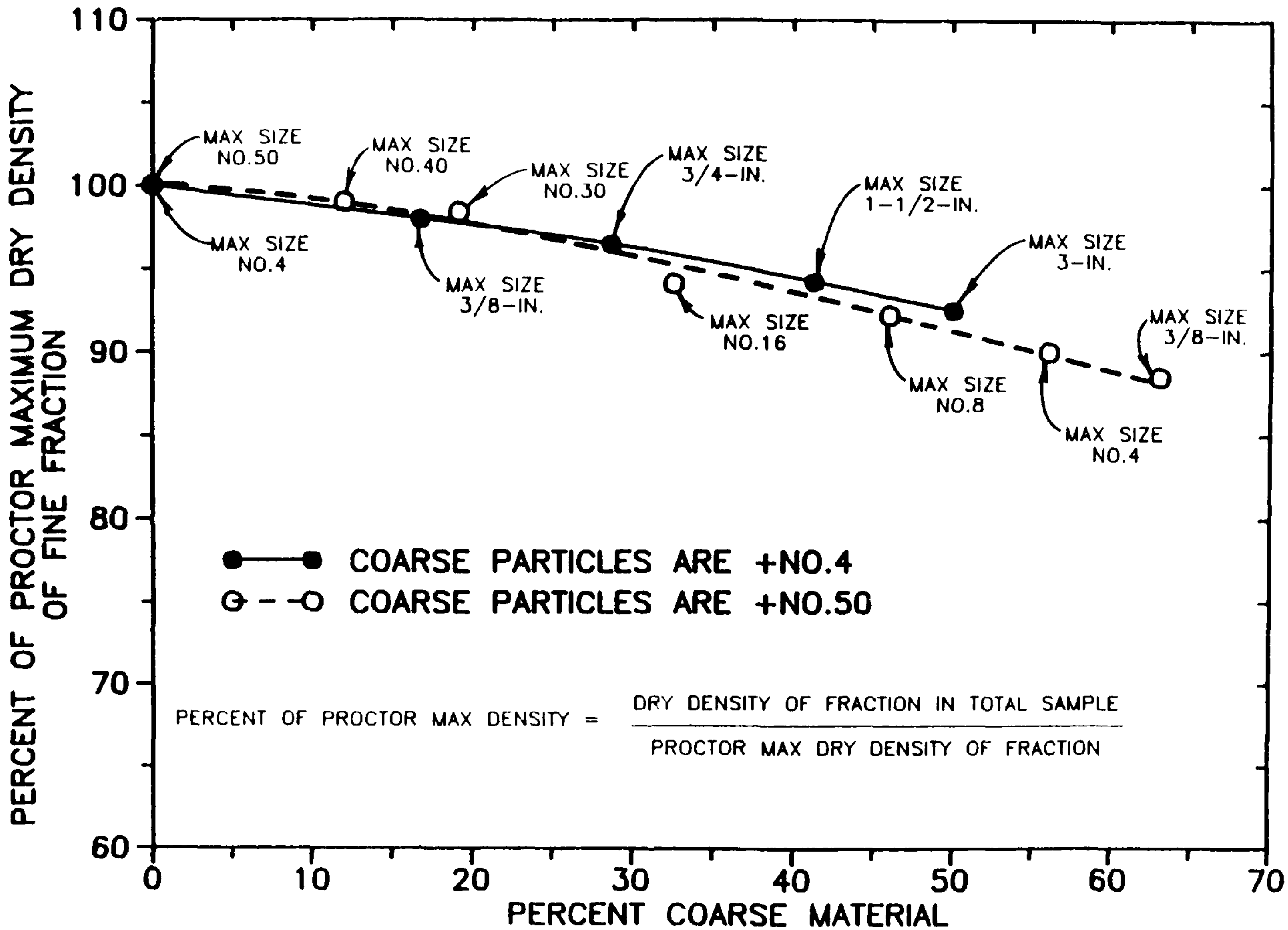


Figure 16. Percent maximum dry density versus percent coarse material (After USBR, 1963)

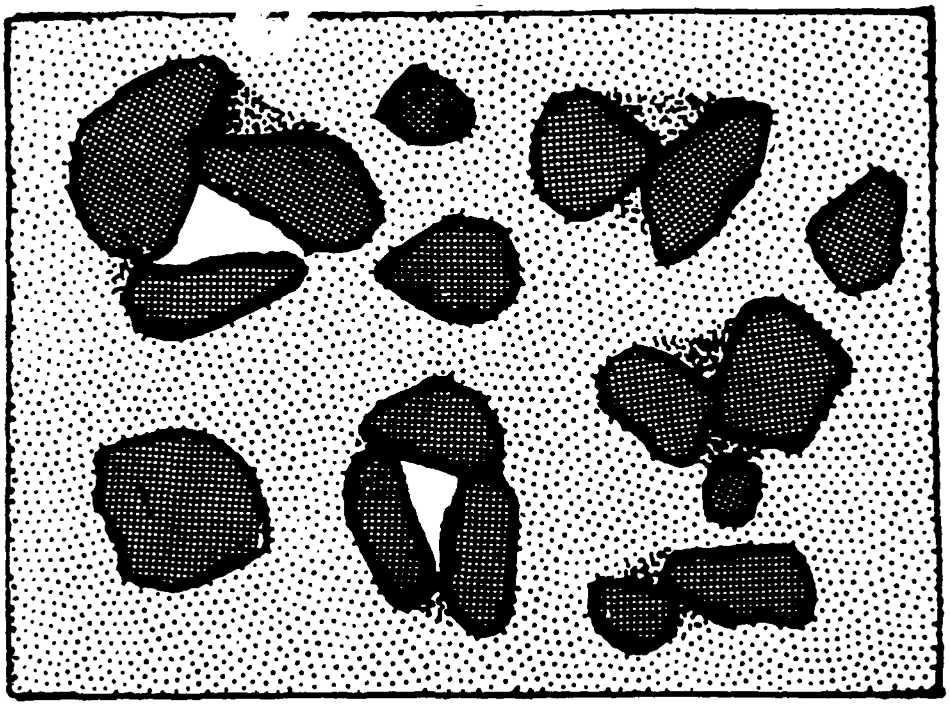


Figure 17. Part of voids assigned to fine fraction and part to coarse gravel fraction (After USBR, 1963)

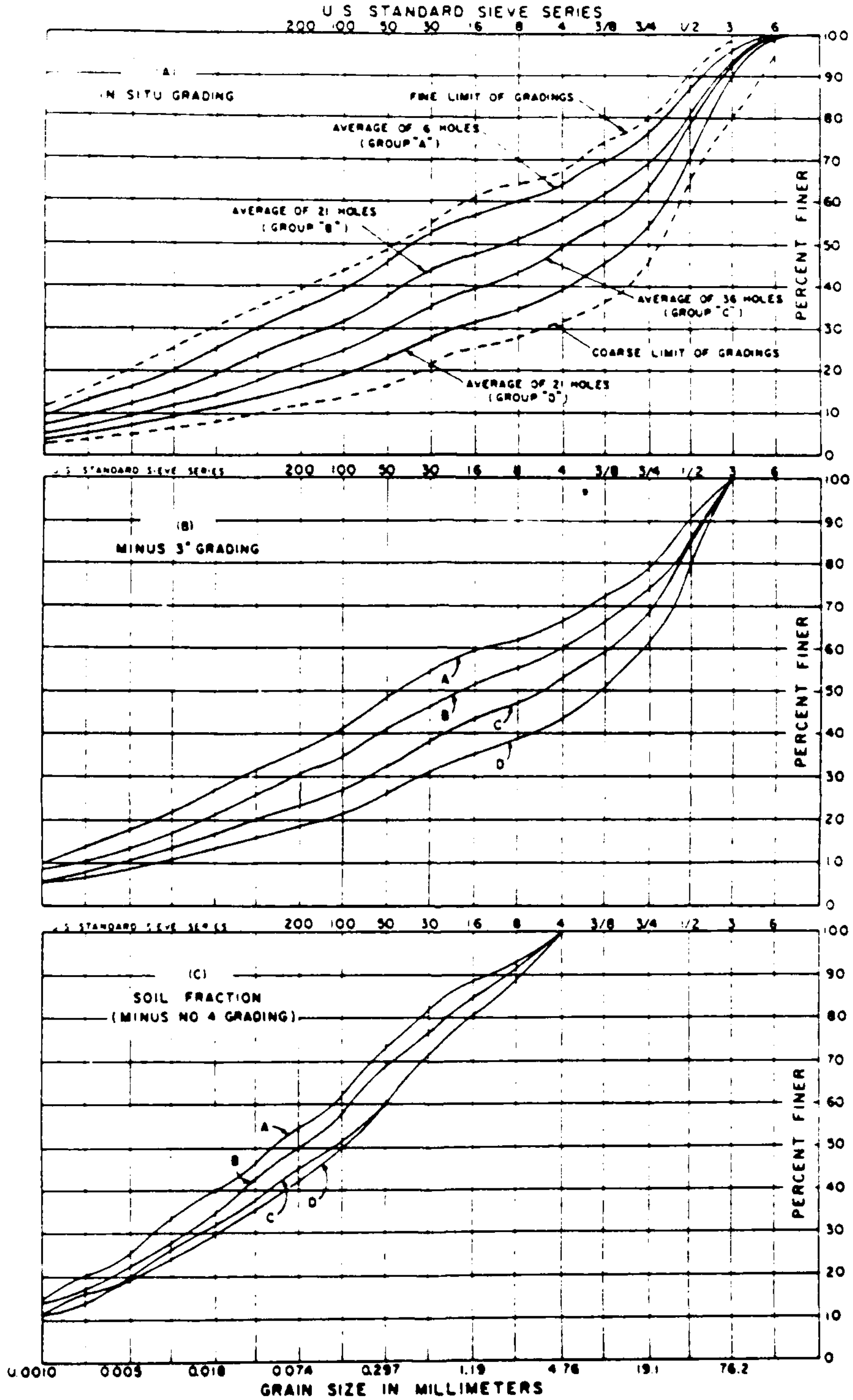
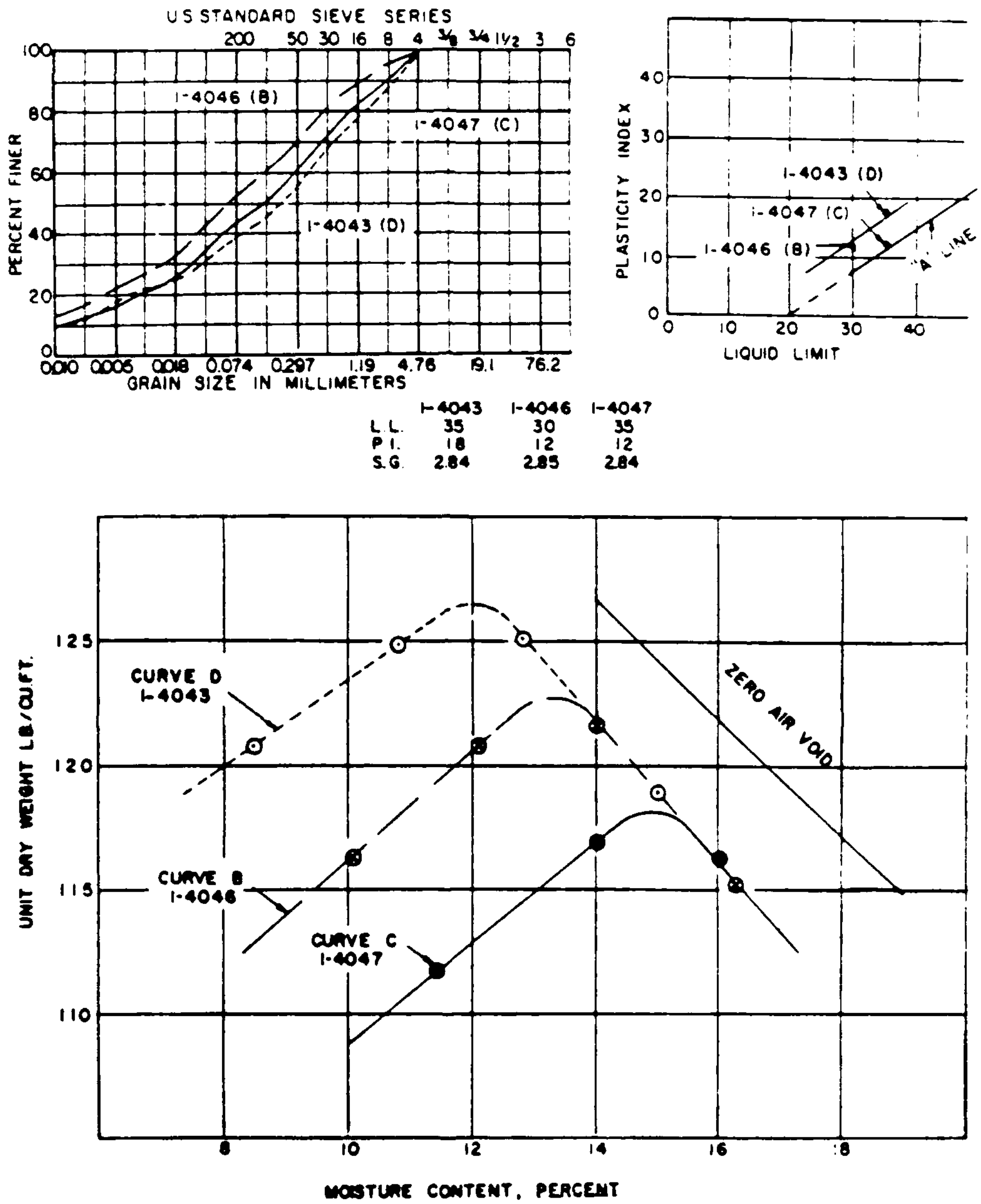


Figure 18. Grading curves representing range of materials (After Gordon, Hammond and Miller, 1965)



	1-4043	1-4046	1-4047
L.L.	35	30	35
P.I.	18	12	12
S.G.	2.84	2.85	2.84

Figure 19. Compaction characteristics of minus No. 4 fraction (After Gordon, Hammond and Miller, 1965)

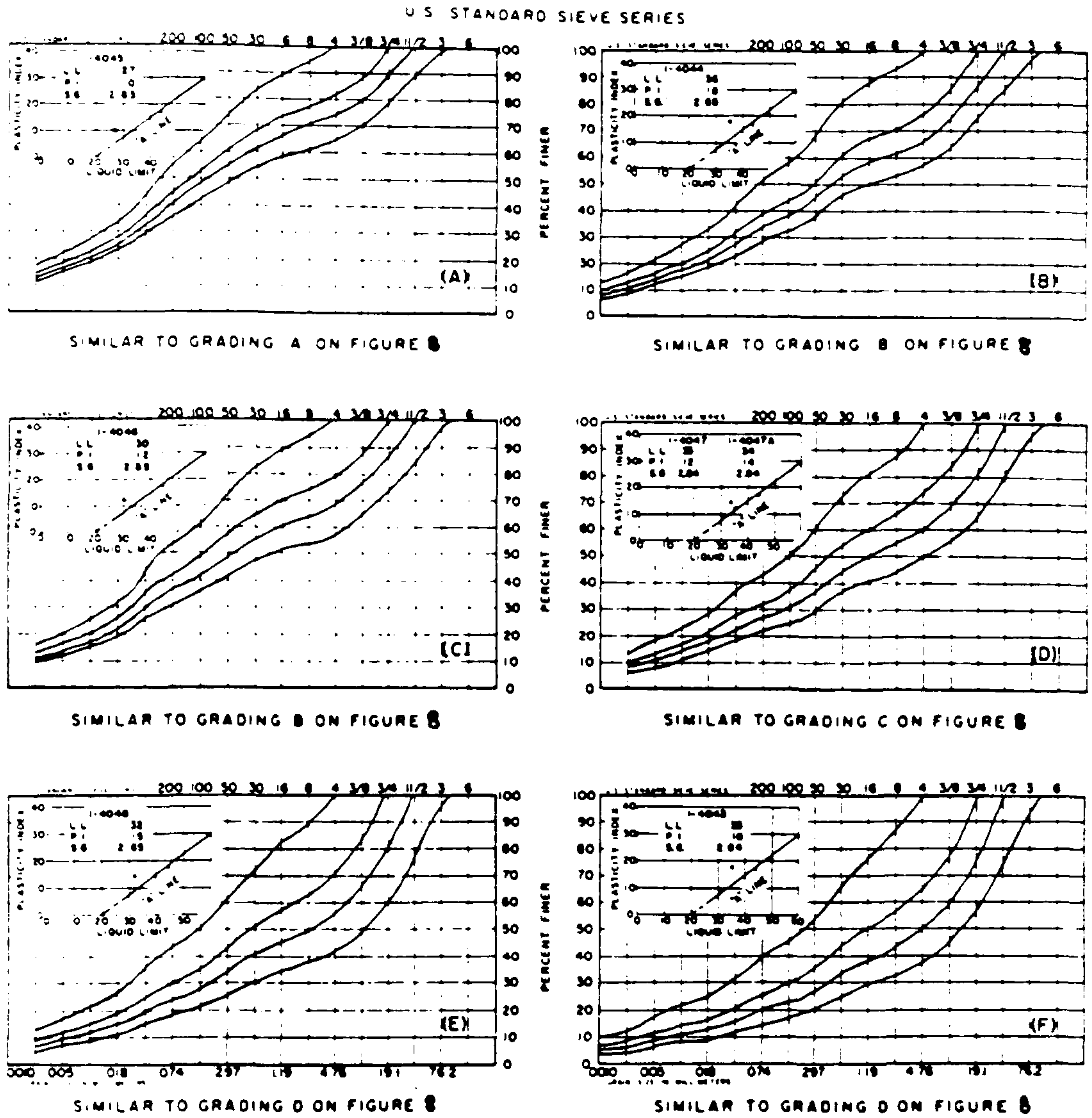


Figure 20. Grading curves for compaction tests in Figure 21 (After Gordon, Hammond and Miller, 1965)

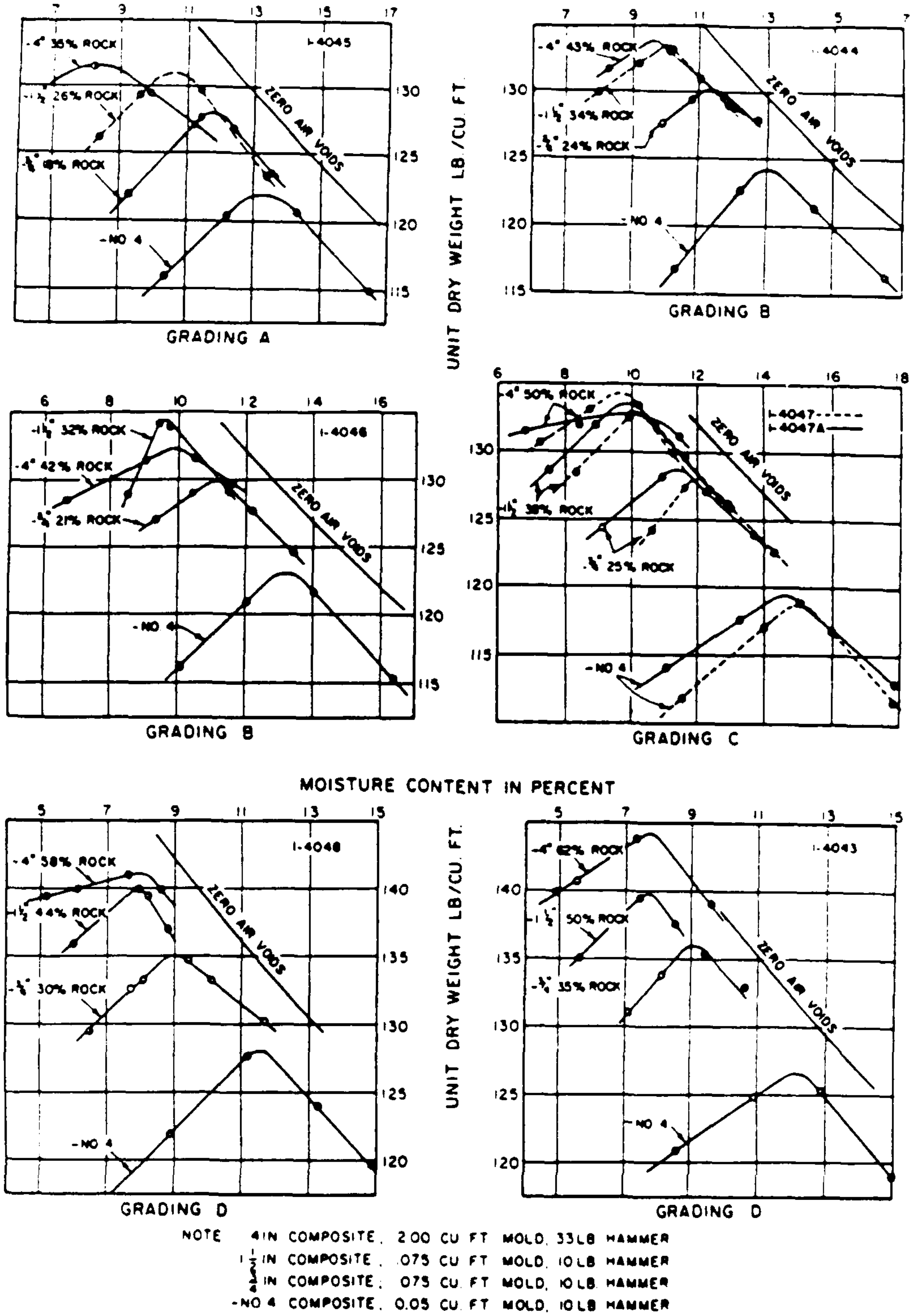


Figure 21. Compaction characteristics of airport borrow material (After Gordon, Hammond and Miller, 1965)

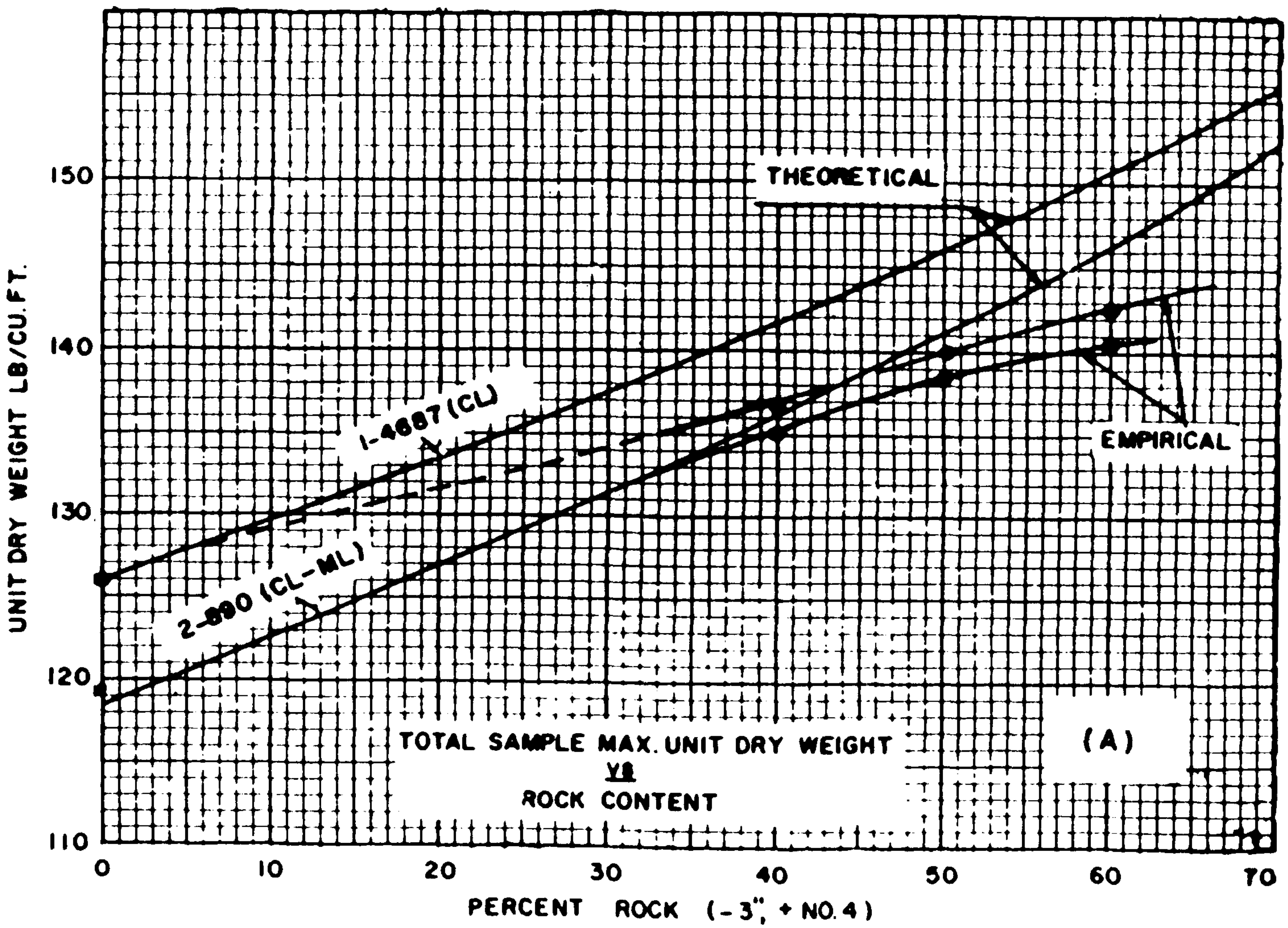


Figure 22. Maximum unit dry weight versus rock content
(After Hammond and Miller, 1965)

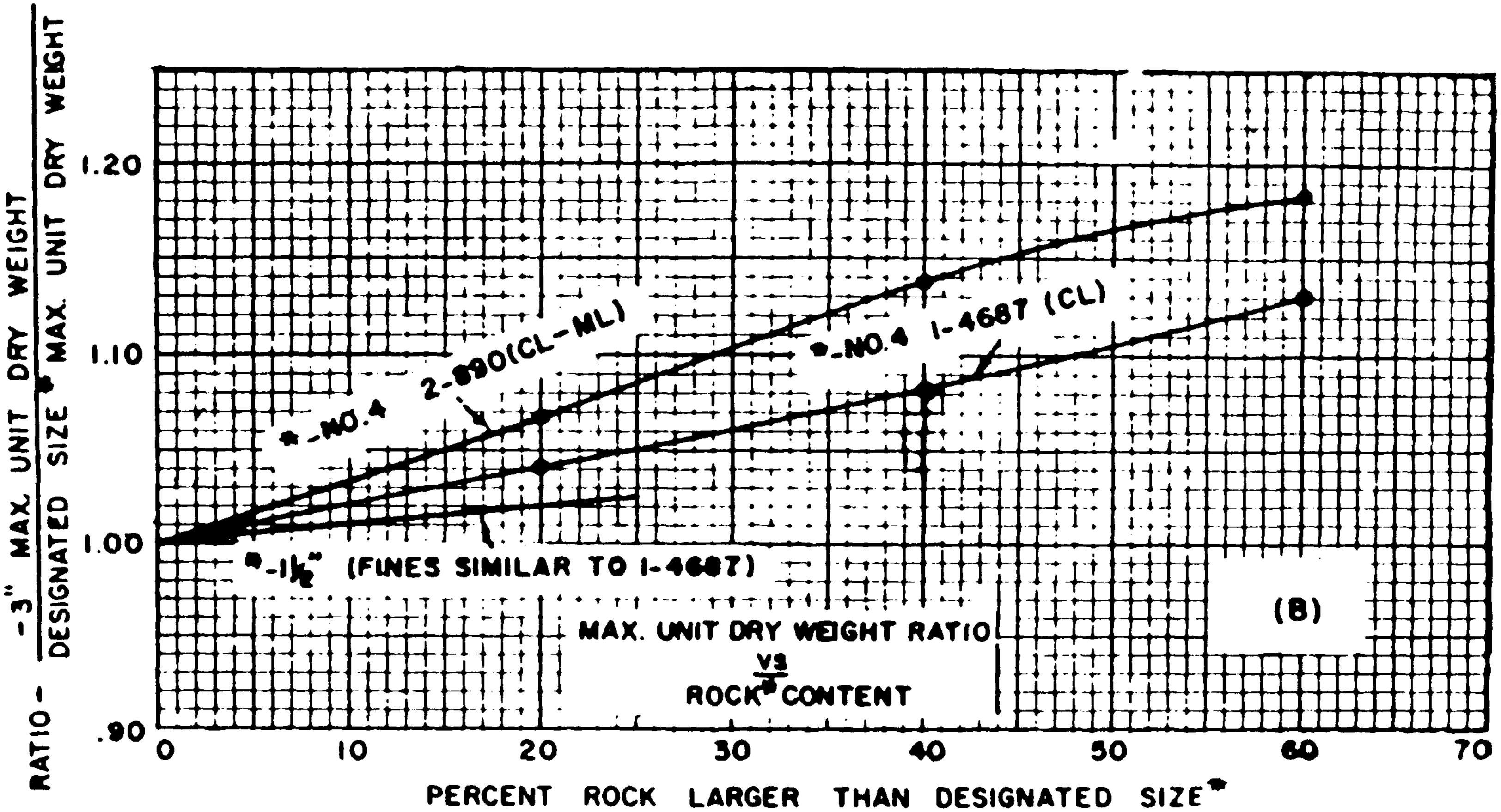


Figure 23. Maximum unit dry weight ratio versus rock content (After Gordon, Hammond and Miller, 1965)

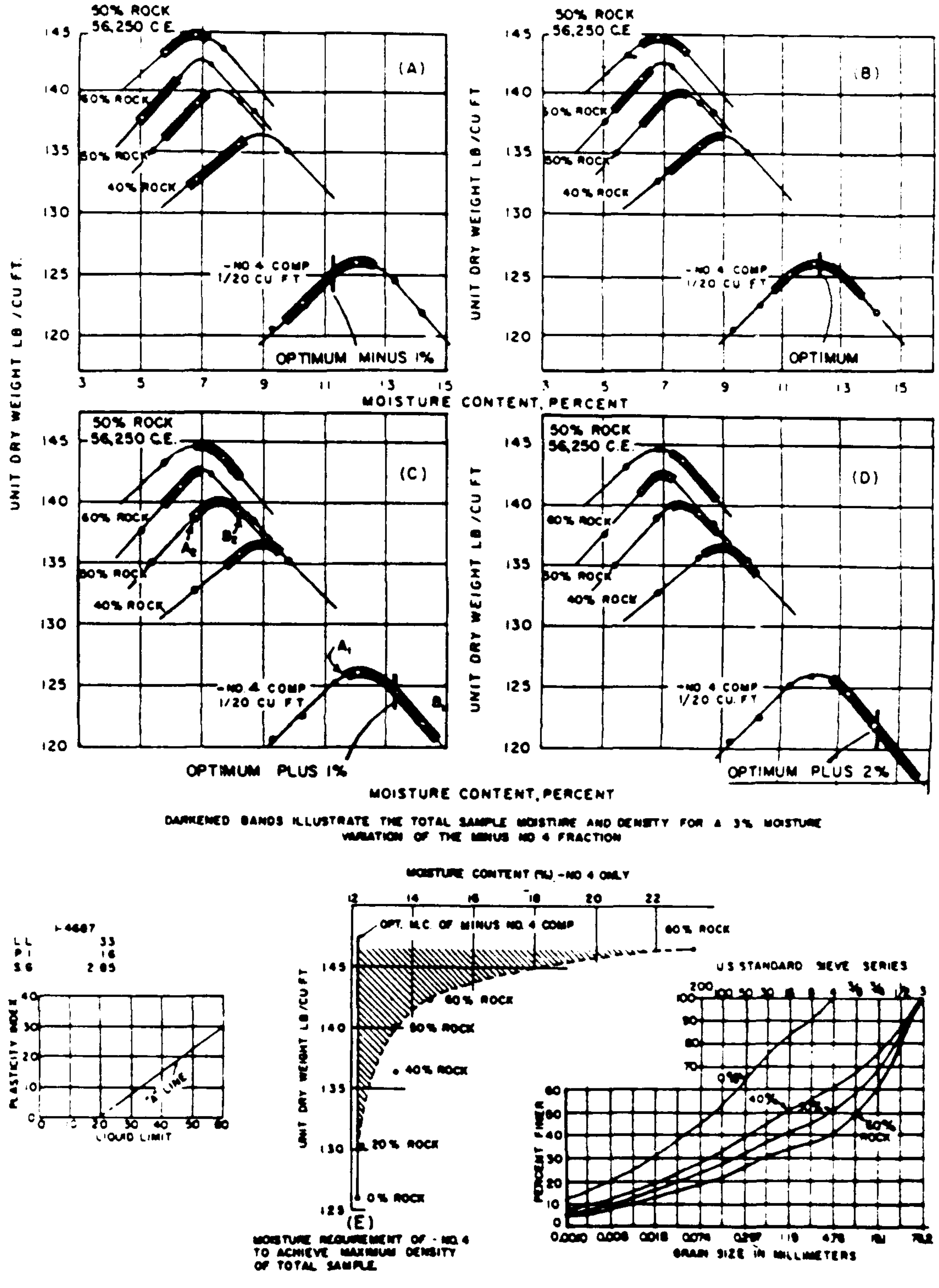


Figure 24. Influence of minus No.4 moisture content on total sample dry density (After Gordon, Hammond and Miller, 1965)

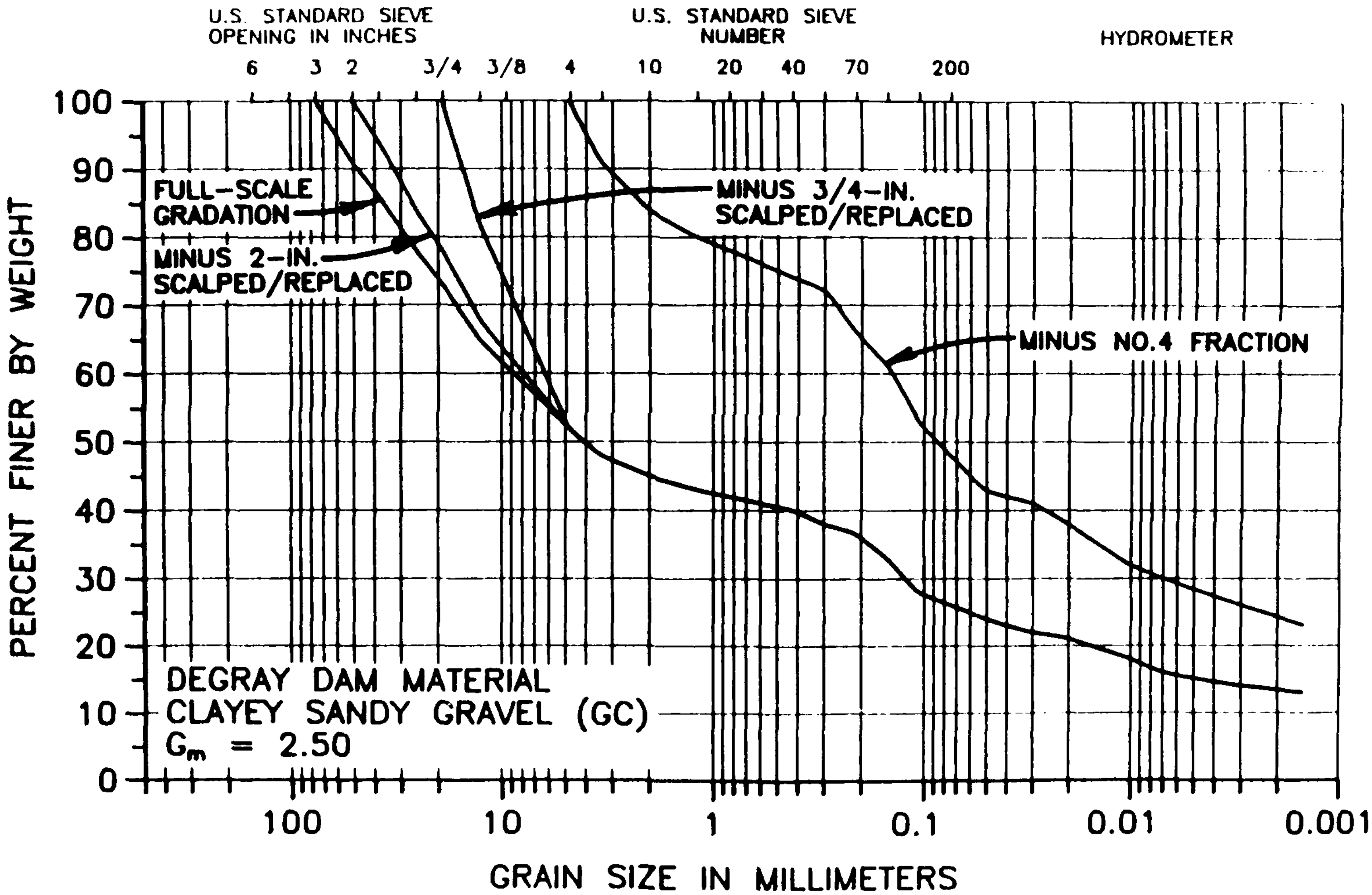


Figure 25. Grain-size distribution curves and classification data, clayey sandy gravel from Degray Dam (After Donaghe and Townsend, 1973)

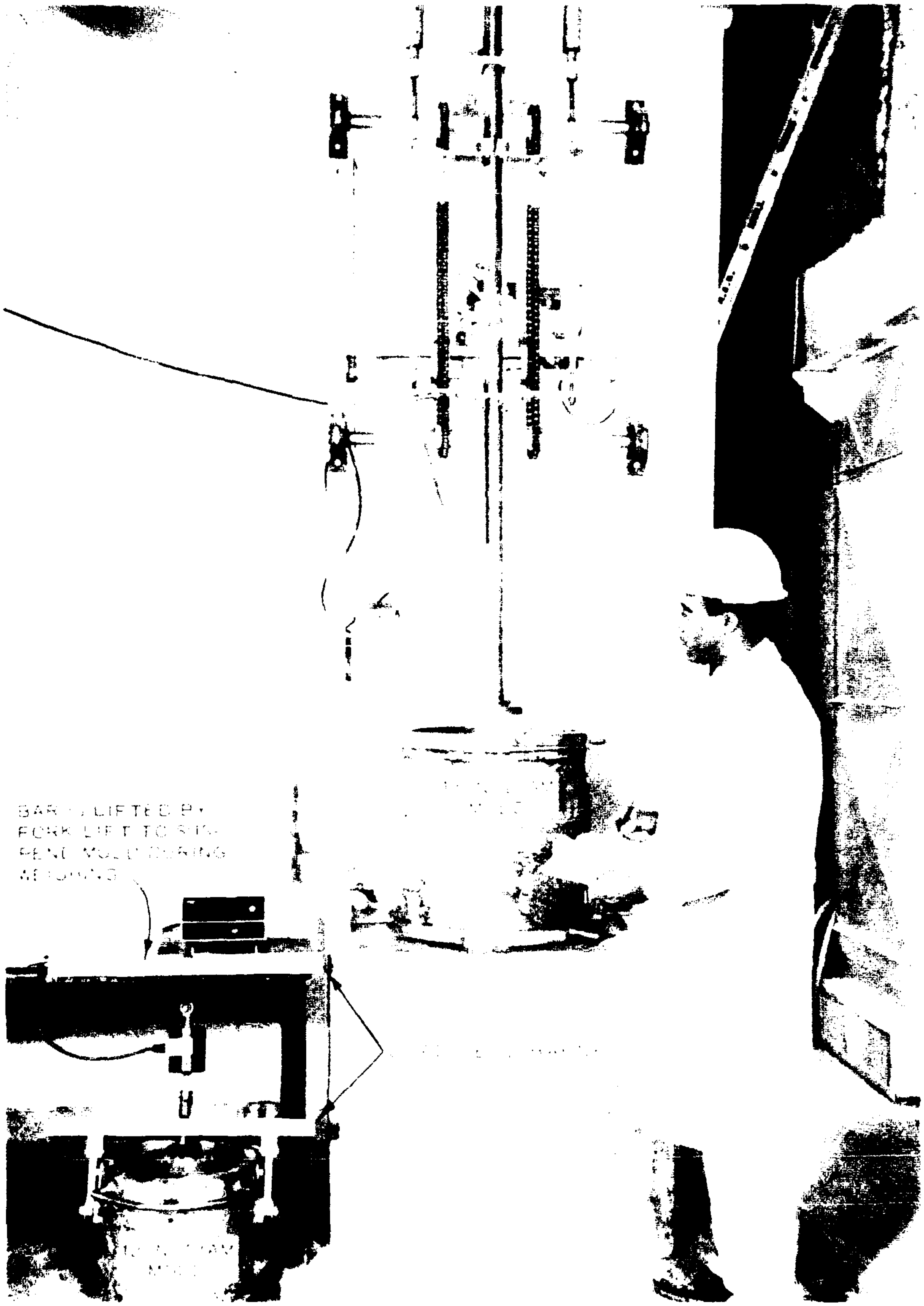
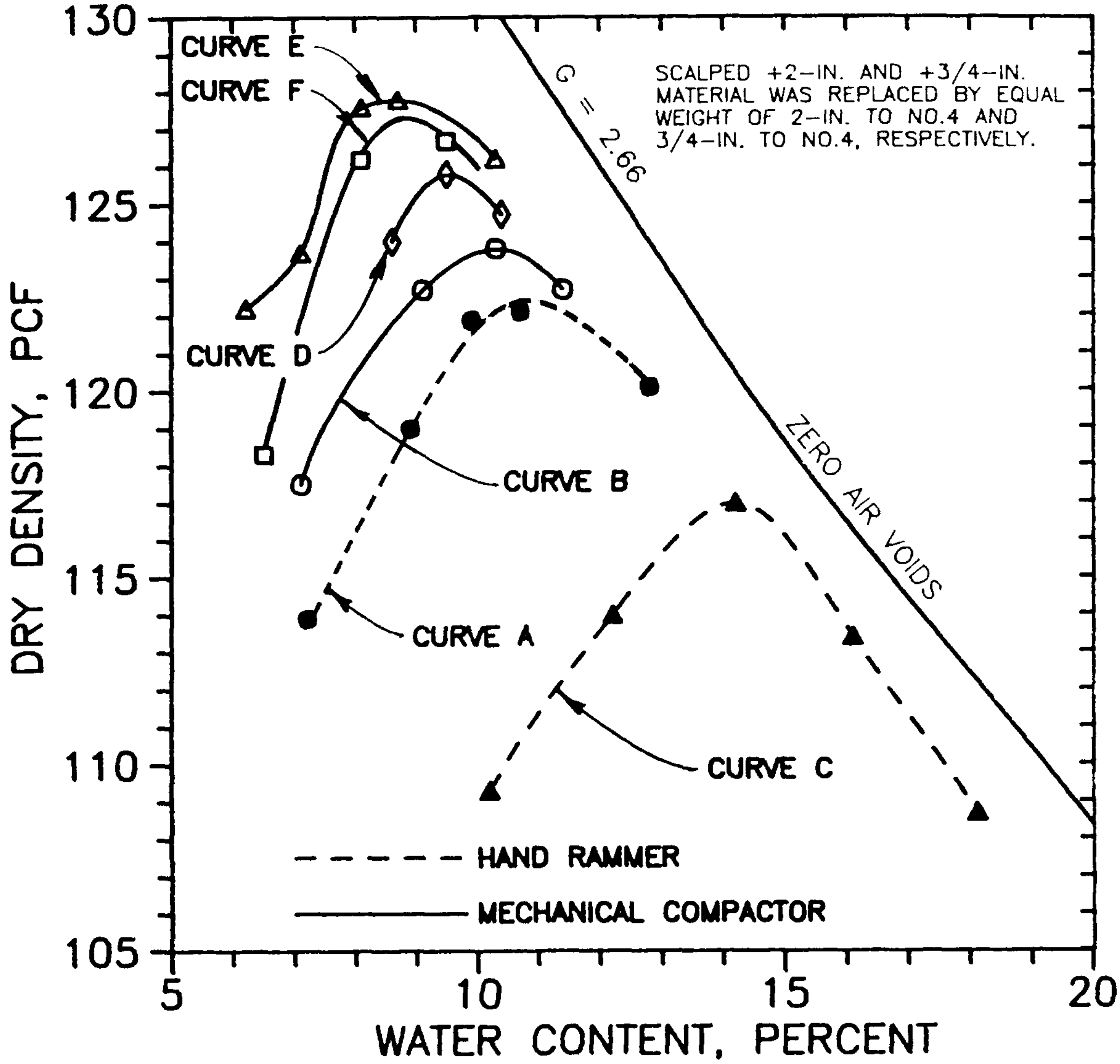


Figure 26. Howard mechanical compactor with 12- and 18-in. diameter molds and load cell harness for weighing (After Donaghe and Townsend, 1973)



	HAND RAMMER		MECHANICAL COMPACTOR			
SYMBOL	▲	●	○	□	△	◇
MOLD DIAMETER, IN.	4	6	6	12	18	18
MAXIMUM PARTICLE SIZE	NO.4	3/4"	3/4"	2"	3"	3/4"
OPTIMUM WATER CONTENT PERCENT	14.2	10.8	10.3	8.9	8.7	9.5
MAXIMUM DRY DENSITY PCF	117.0	122.4	123.6	127.3	127.9	125.8

Figure 27. Compaction curves, DeGray clayey sandy gravel compacted by hand-held rammer and mechanical compactor (After Donaghe and Townsend, 1963)

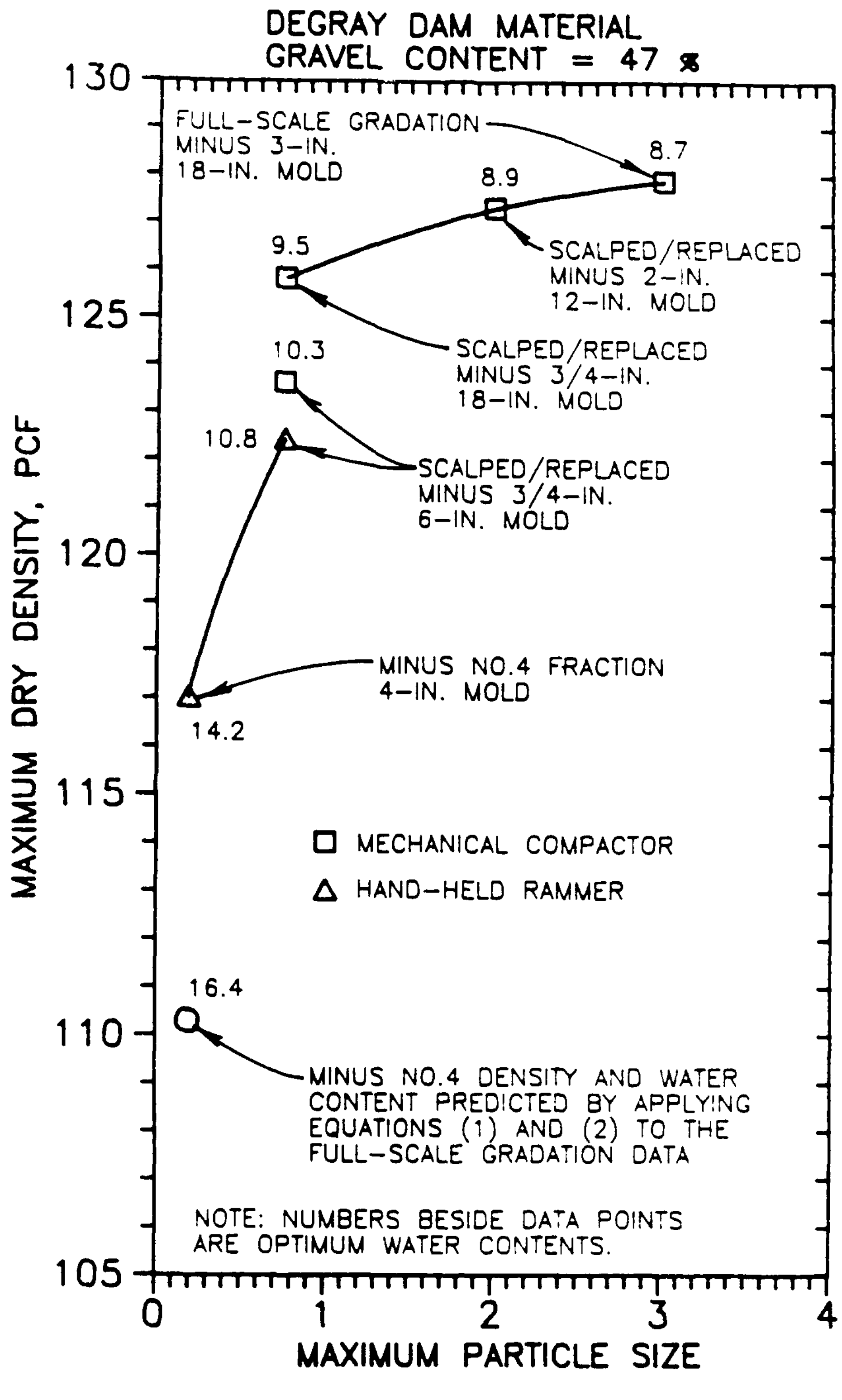


Figure 28. Comparisons of maximum dry densities and optimum water contents for full-scale and scalped/replaced specimens, DeGray clayey sandy gravel

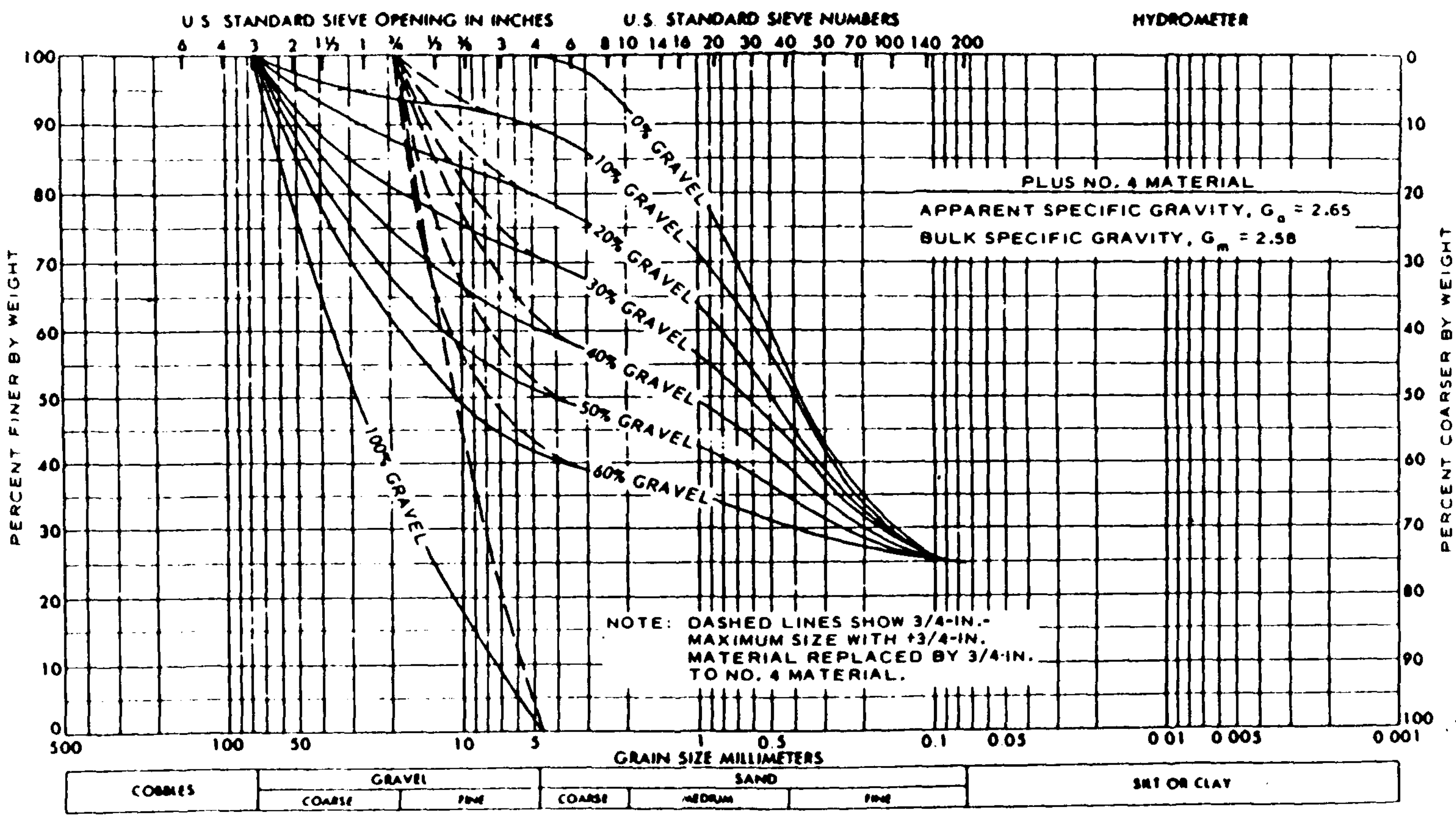
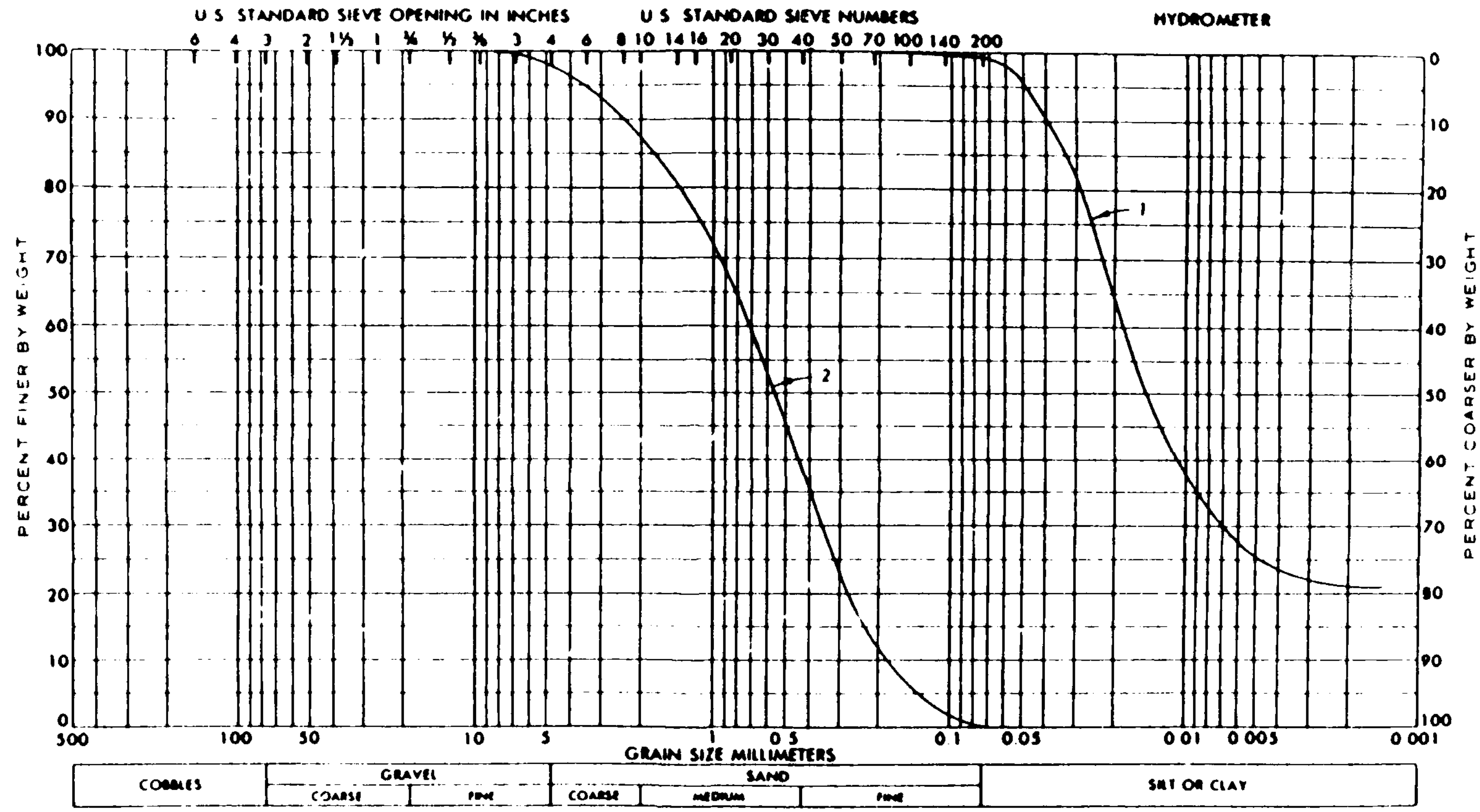


Figure 29. Test gradations to study effects of gravel content (After Donaghe and Townsend, 1975)



SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
1		CLAY (CL)		43	22	21
2		SAND (SP)		NP	NP	NP

Figure 30. Grain-size distribution curves and classification data, clay (CL) and sand (SP) (After Donaghe and Townsend, 1975)

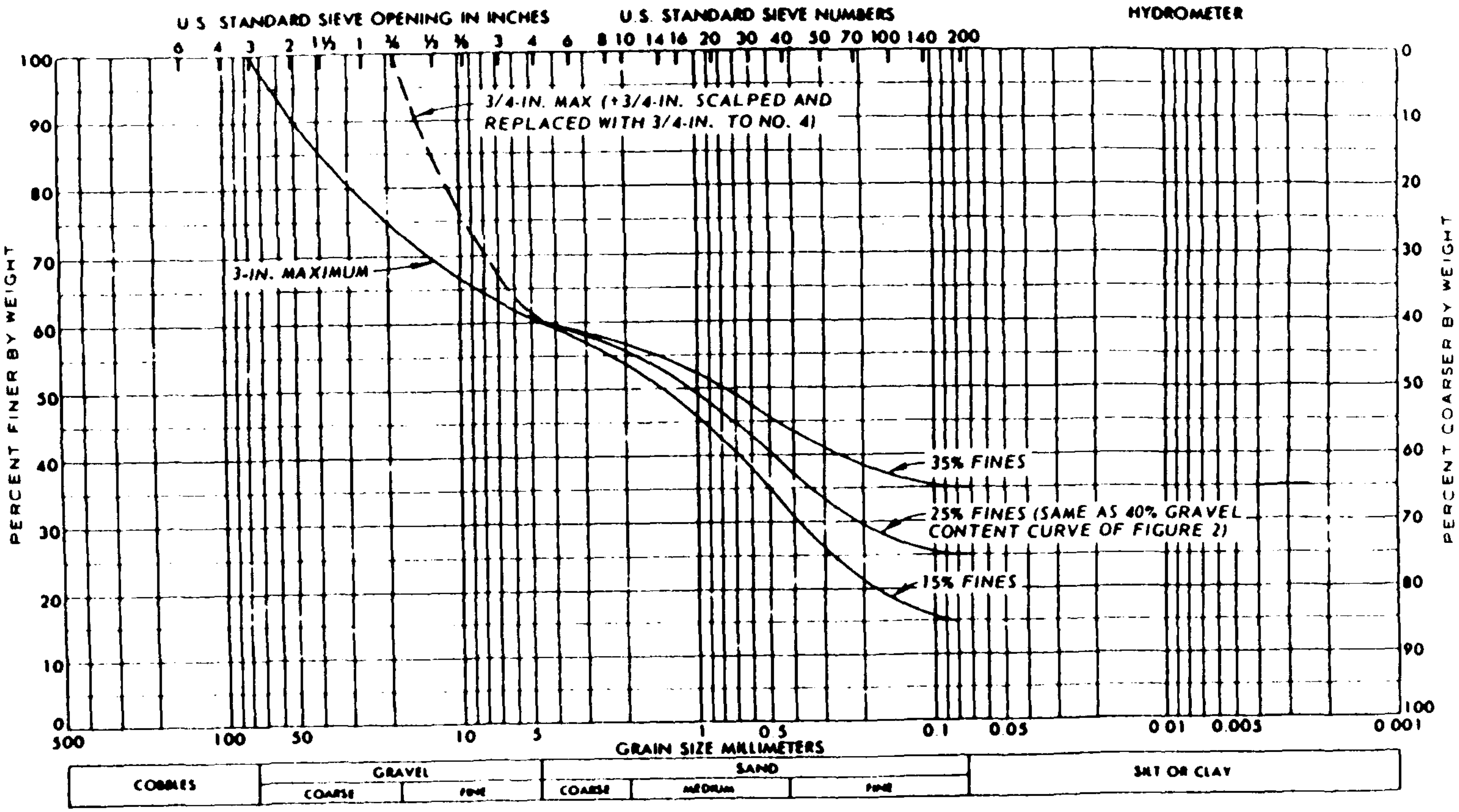


Figure 31. Test gradations to study effects of fines content (After Donaghe and Townsend, 1975)

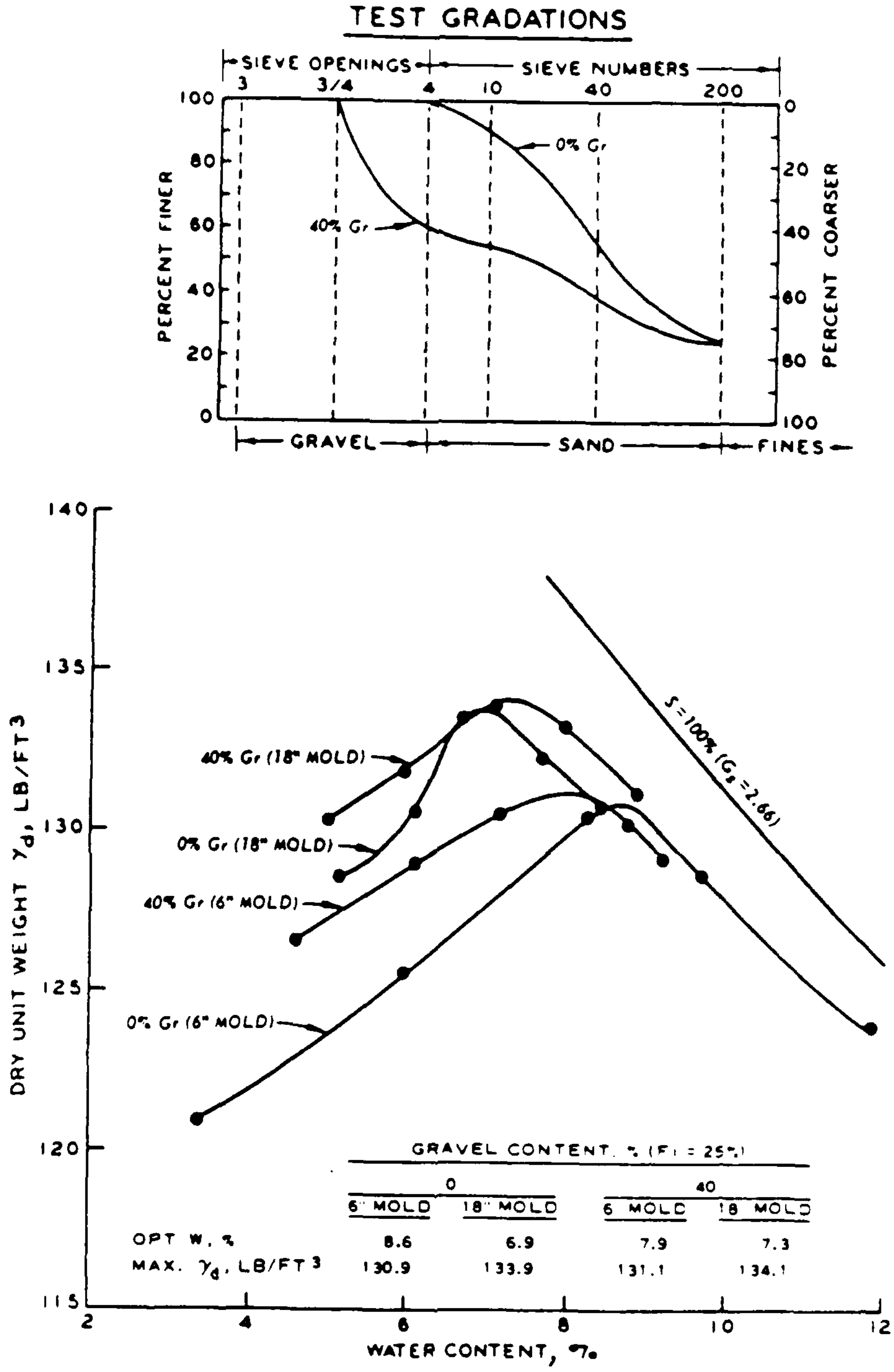


Figure 32. Compaction curves for tests to determine effects of varying mold diameter (After Donaghe and Townsend, 1975)

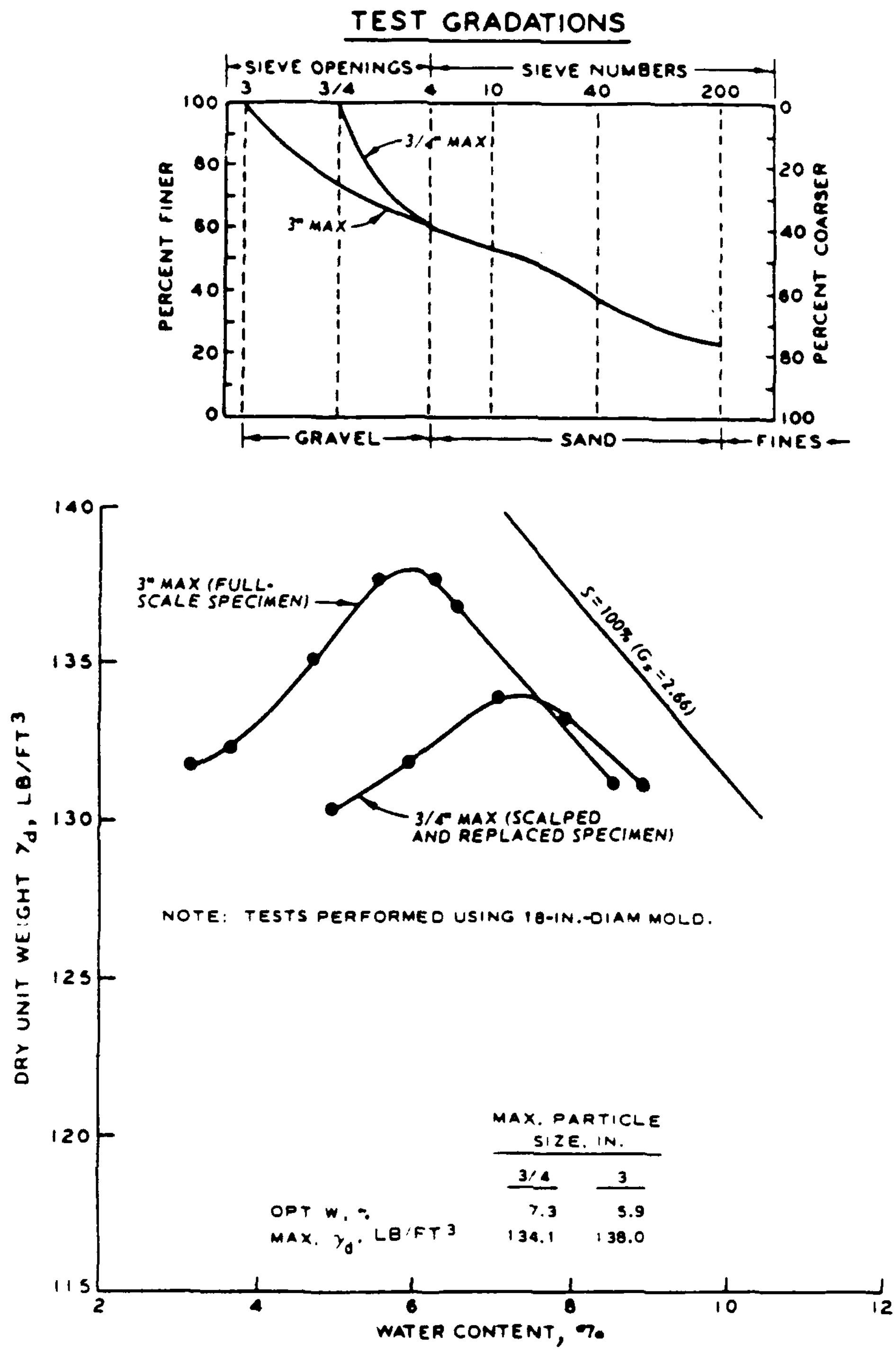
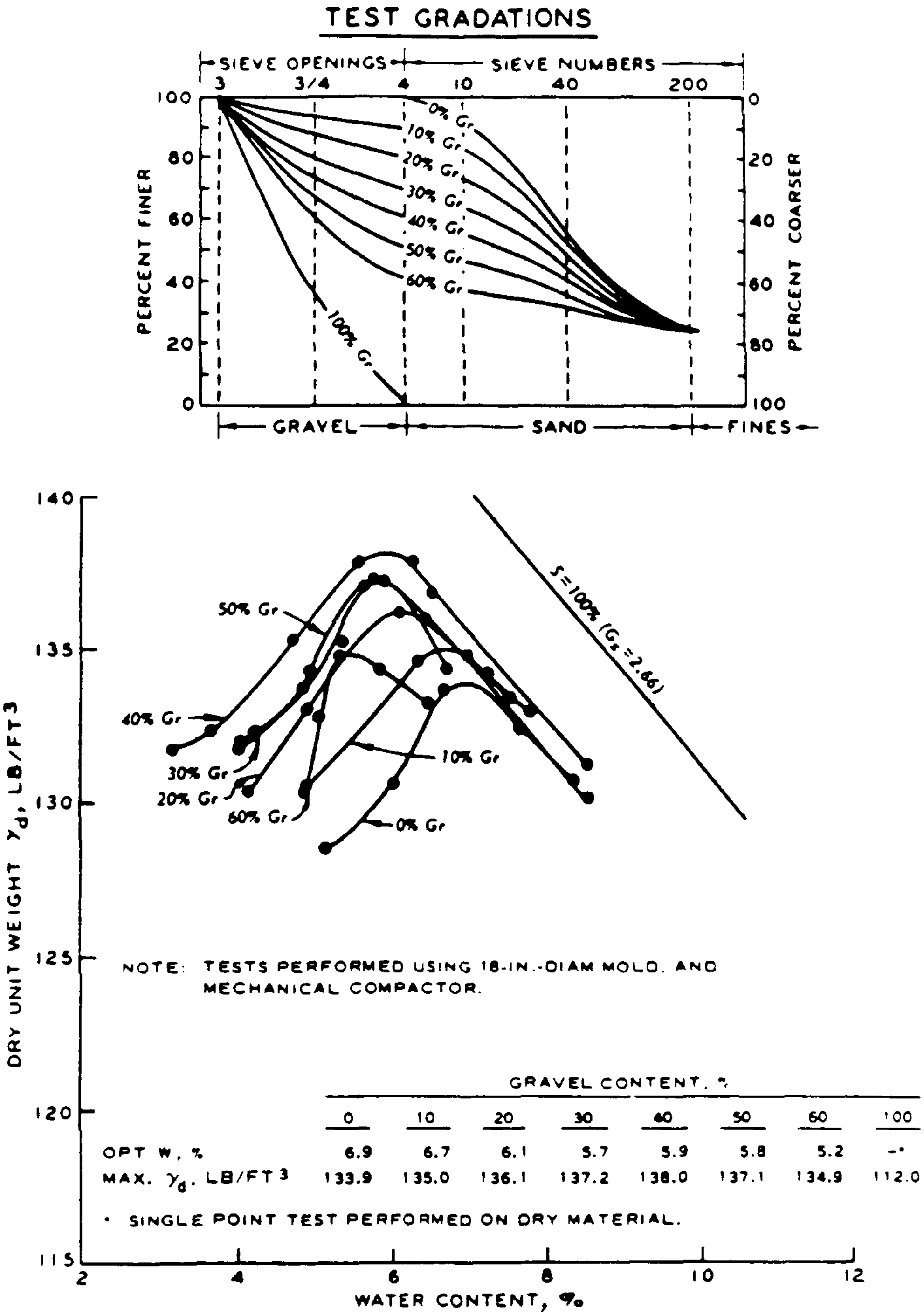


Figure 33. Compaction curves for tests to determine effect of removal and replacement of oversize particles (After Donaghe and Townsend,1975)



	GRAVEL CONTENT, %							
	0	10	20	30	40	50	60	100
OPT w, %	6.9	6.7	6.1	5.7	5.9	5.8	5.2	-*
MAX. γ_d, LB/FT³	133.9	135.0	136.1	137.2	138.0	137.1	134.9	112.0

Figure 34. Compaction curves for tests conducted on full-scale specimens having variable gravel contents (After Donaghe and Townsend, 1975)

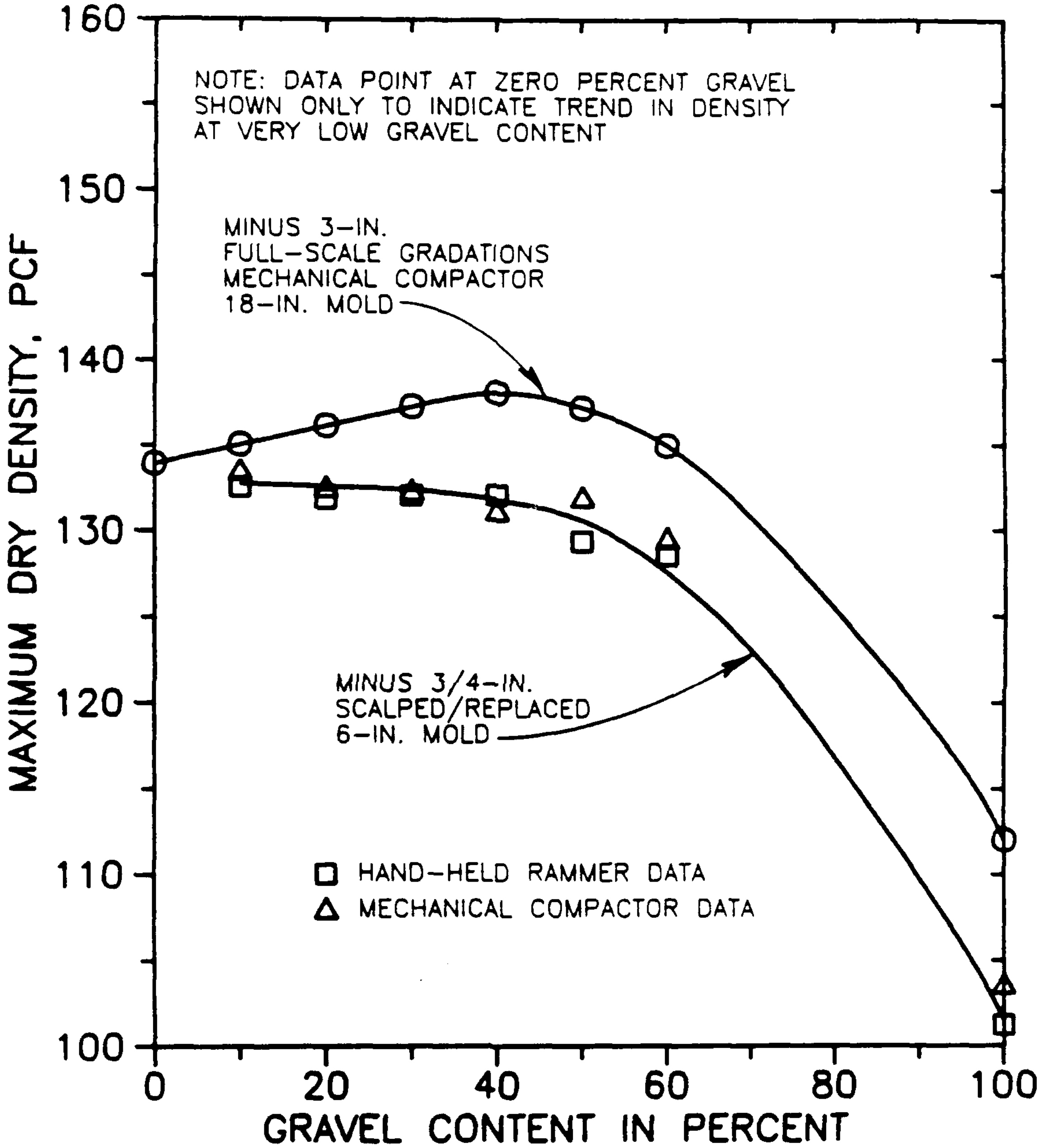
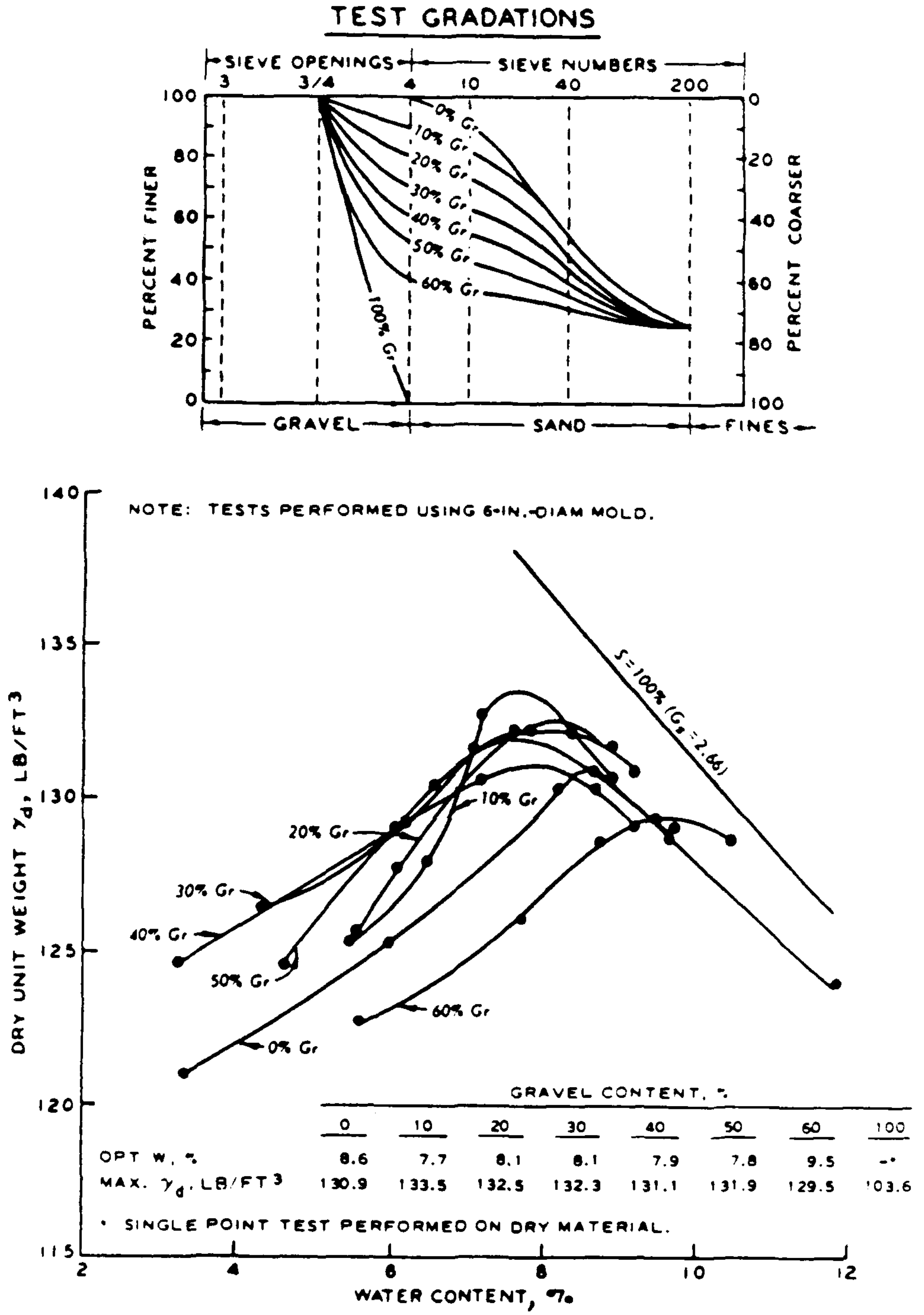


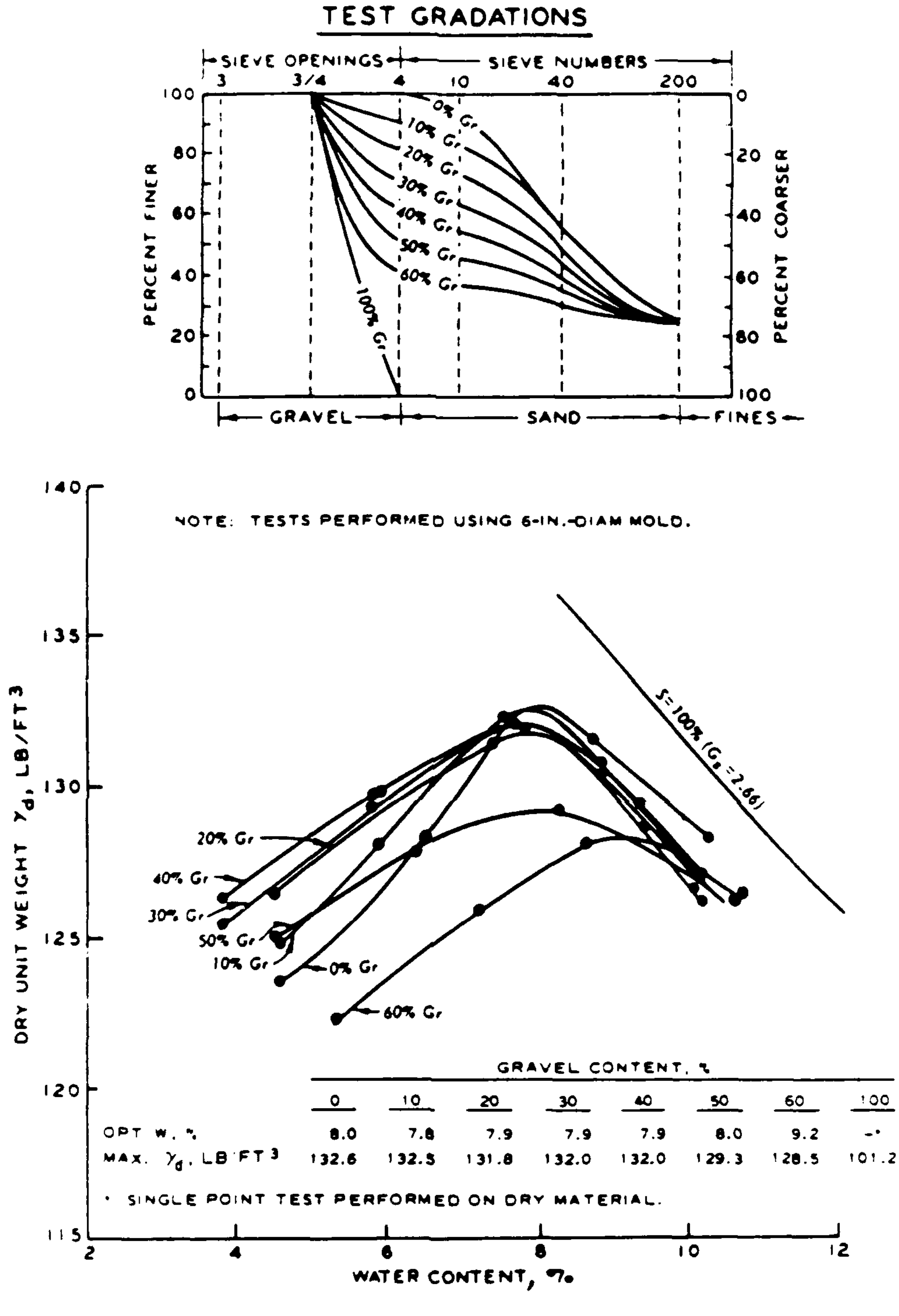
Figure 35. Comparison of full-scale and minus 3/4-in. scalped and replaced maximum dry densities for gradations with variable gravel content (After Donaghe and Townsend, 1975)



	GRAVEL CONTENT, %							
	0	10	20	30	40	50	60	100
OPT w, %	8.6	7.7	8.1	8.1	7.9	7.8	9.5	--*
MAX. γ_d, LB/FT 3	130.9	133.5	132.5	132.3	131.1	131.9	129.5	*103.6

* SINGLE POINT TEST PERFORMED ON DRY MATERIAL.

Figure 36. Compaction curves for small-scale tests conducted on specimens having scalped and replaced coarse particles with variable gravel contents, mechanical compactor (After Donaghe and Townsend, 1975)



	0	10	20	30	40	50	60	100
OPT w, %	8.0	7.8	7.9	7.9	7.9	8.0	9.2	-*
MAX. γ_d, LB/FT3	132.6	132.5	131.8	132.0	132.0	129.3	128.5	101.2

Figure 37. Compaction curves for small-scale tests conducted on specimens having scalped and replaced coarse particles with variable gravel contents, hand-held rammer (After Donaghe and Townsend, 1975)

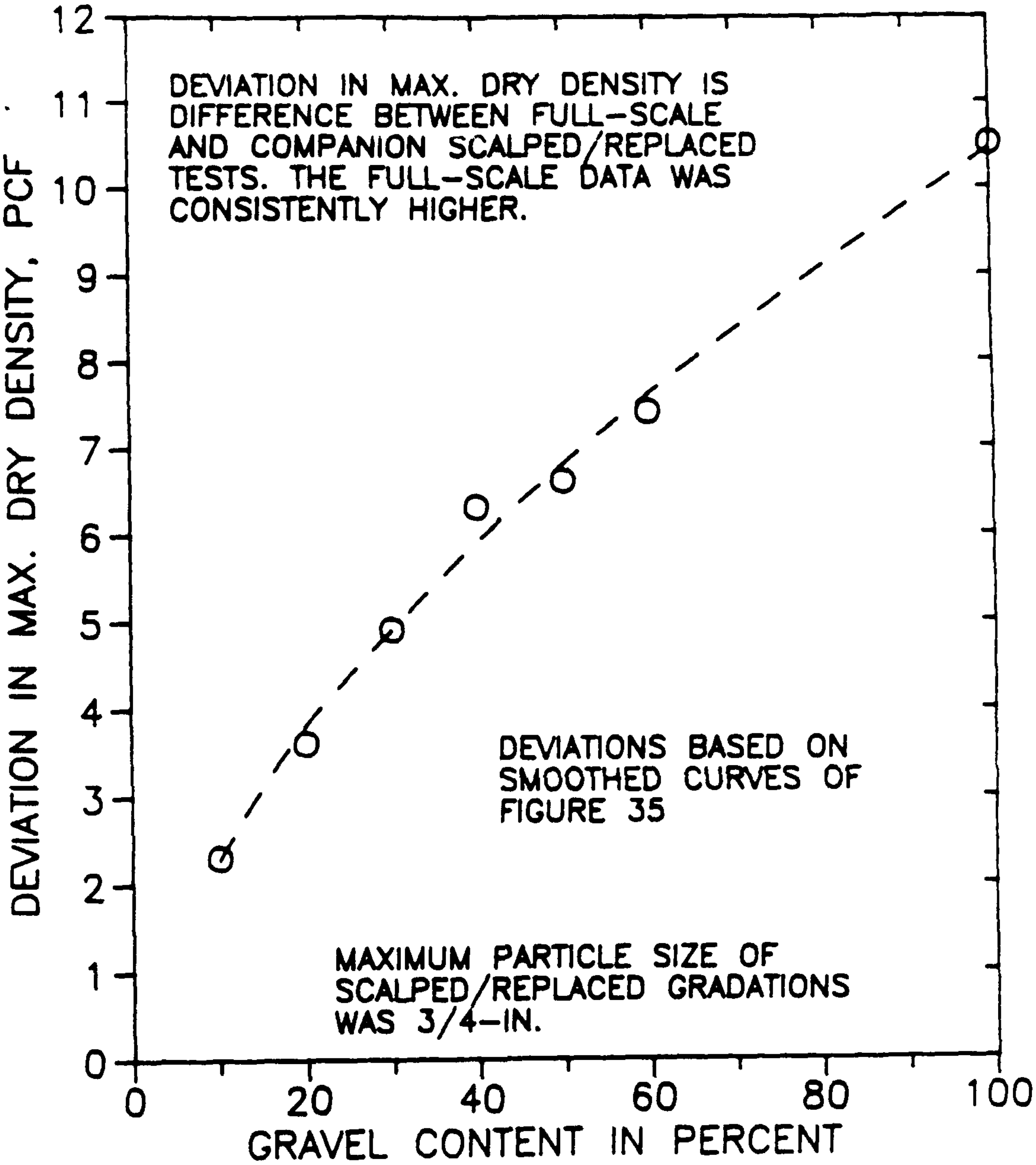


Figure 38. Deviation of scalped/replaced maximum dry densities from those of corresponding full-scale gradations (data from Donaghe and Townsend, 1975)

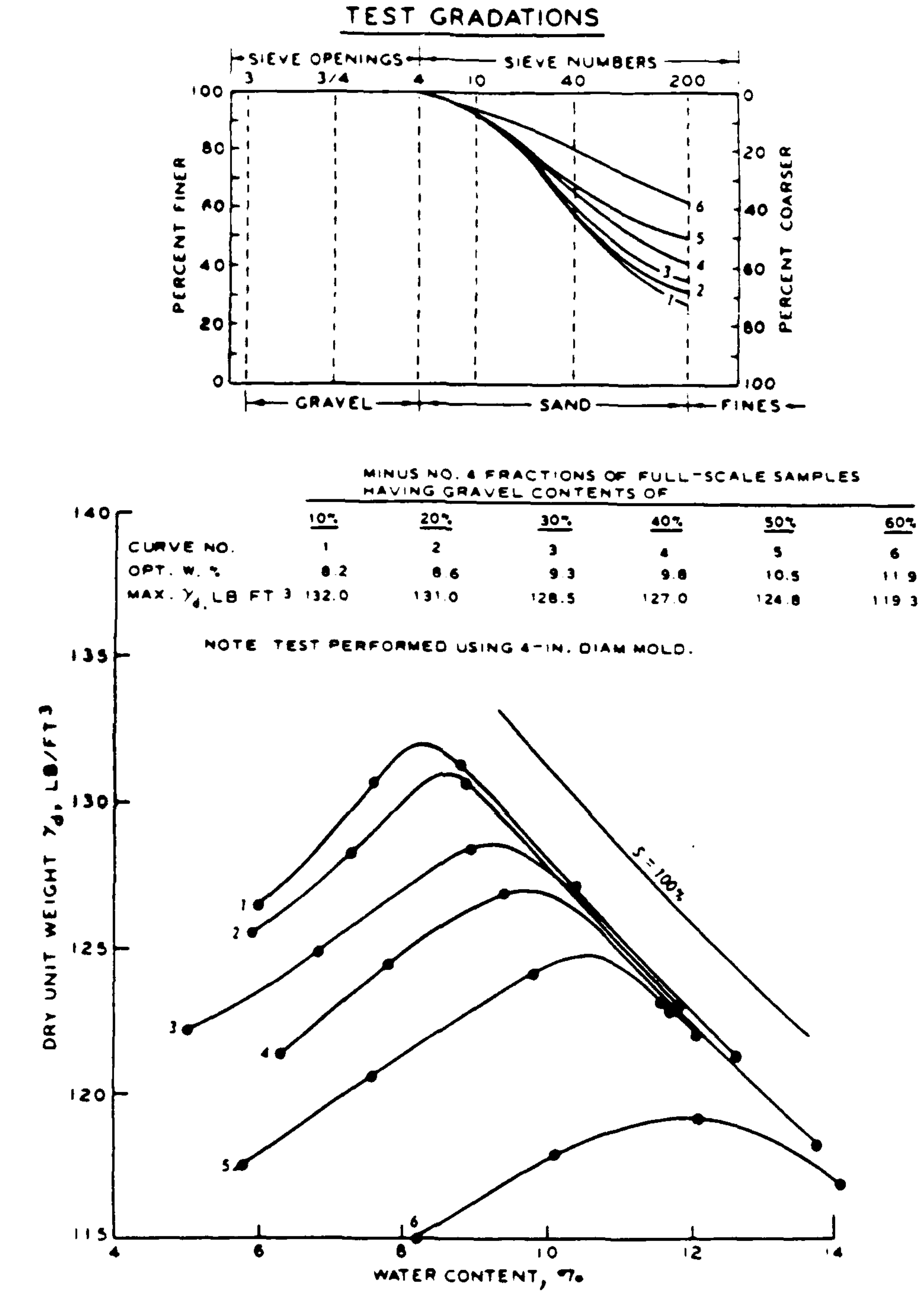


Figure 39. Compaction curves for tests on minus No.4 fractions of full-scale sample series in which gravel content was varied; hand-held rammer (After Donaghe and Townsend, 1975)

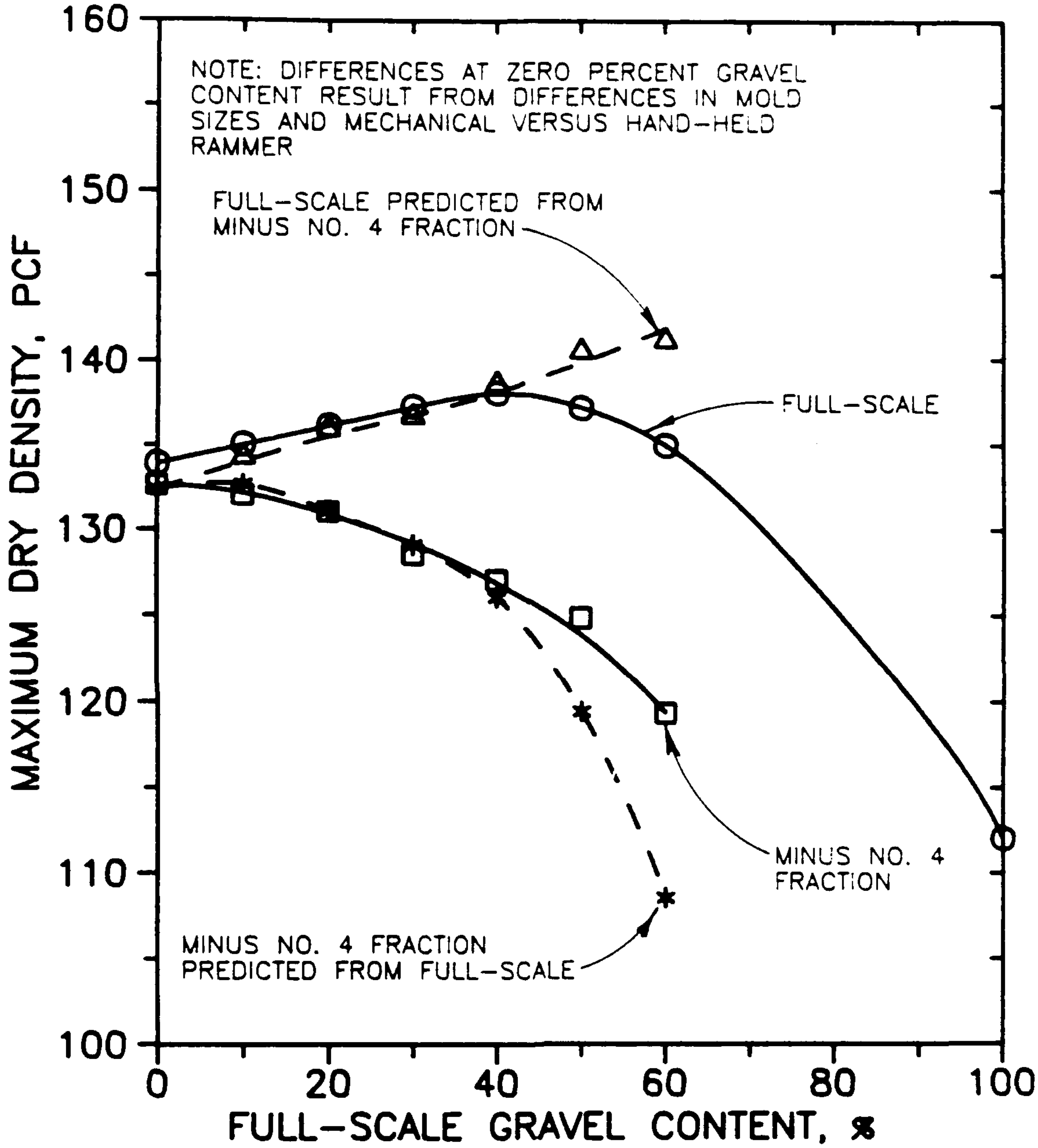


Figure 40. Experimental and theoretical relationships between maximum dry unit weight and gravel content utilizing full-scale and minus No.4 fraction data (After Donaghe and Townsend, 1975)

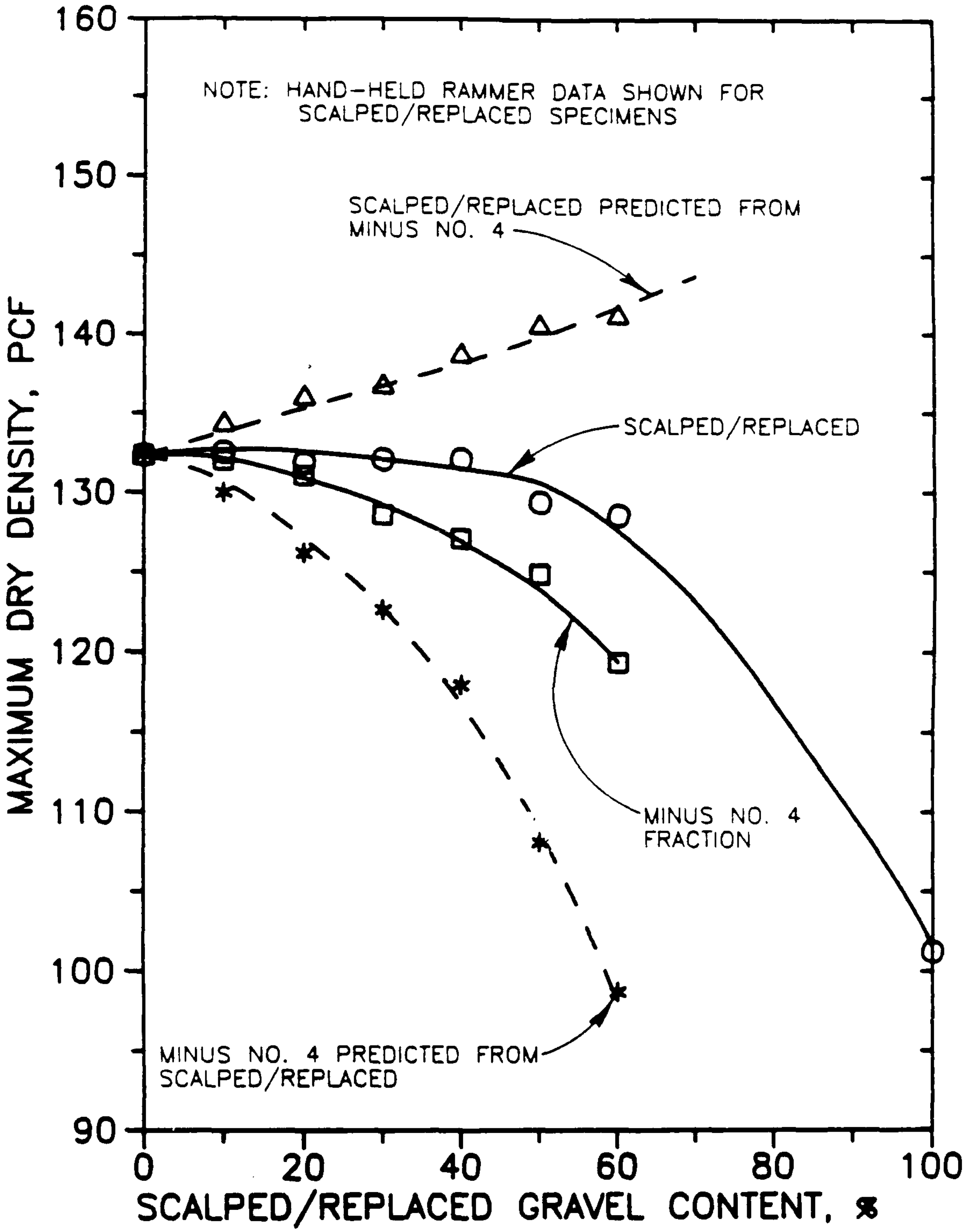


Figure 41. Experimental and theoretical relationships between maximum dry unit weight and gravel content utilizing scalped and replaced and minus No.4 fraction data (data from Donaghe and Townsend, 1975)

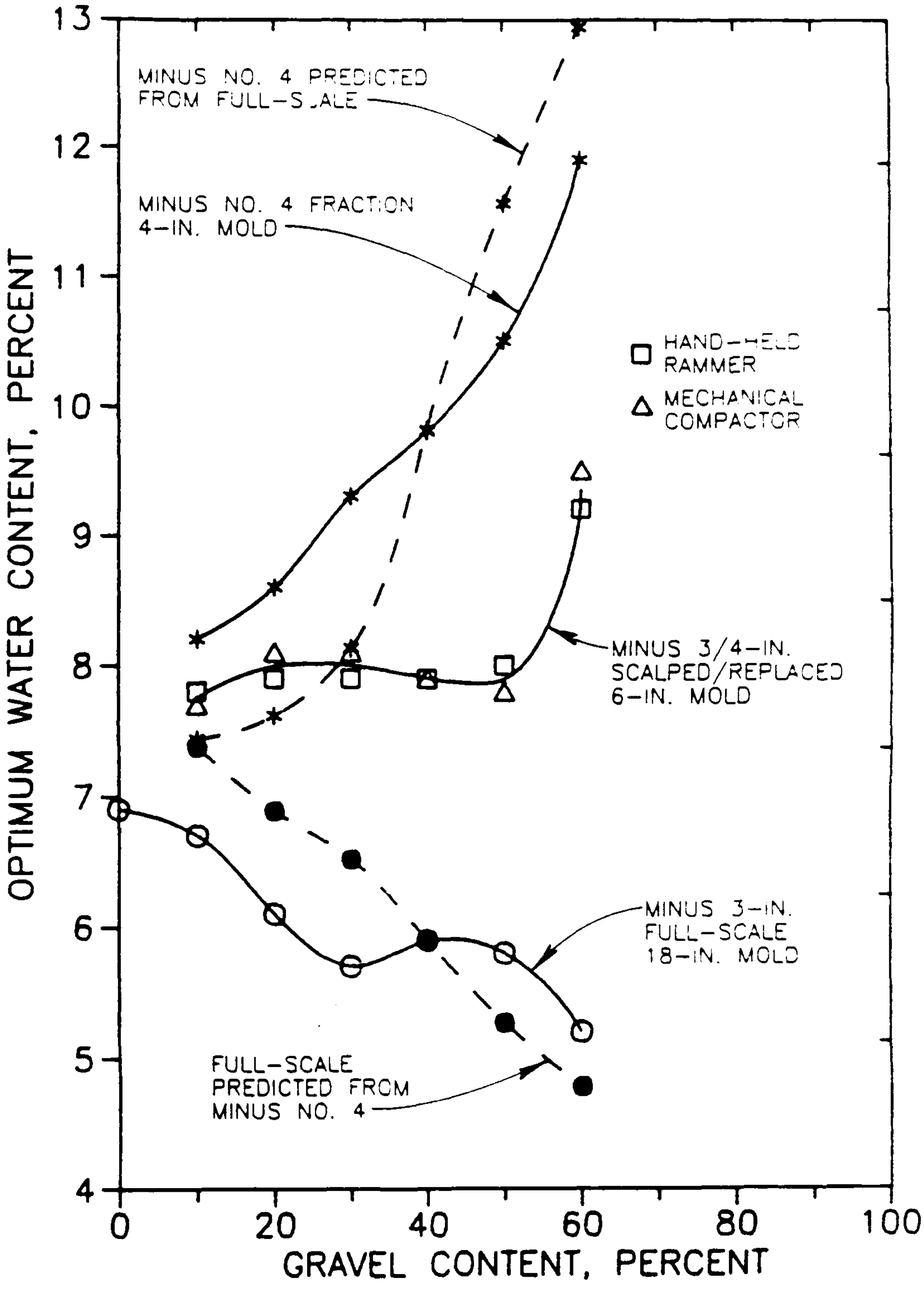


Figure 42. Experimental and theoretical relationships between optimum water content and gravel content (data from Donaghe and Townsend, 1975)

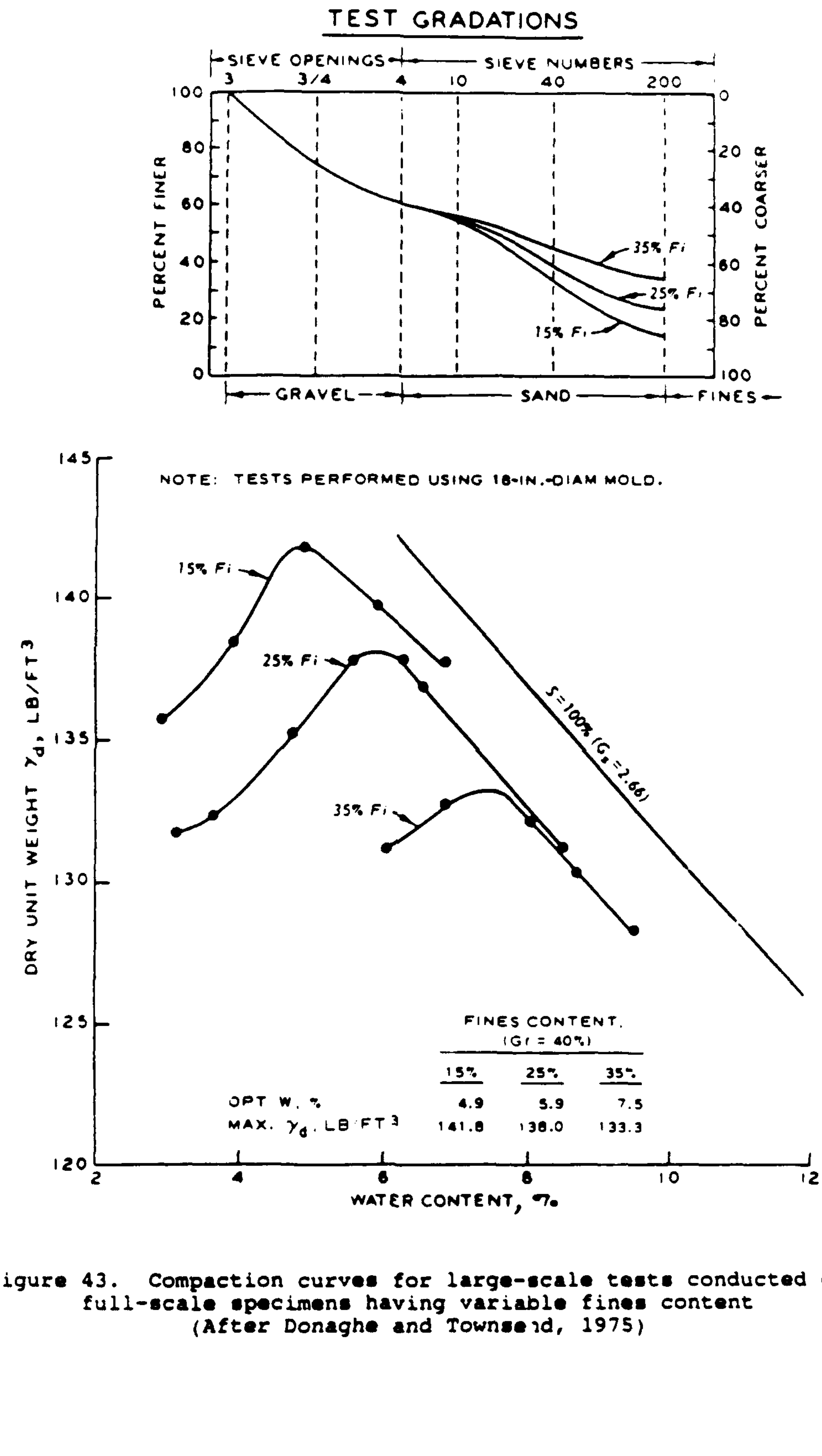


Figure 43. Compaction curves for large-scale tests conducted on full-scale specimens having variable fines content (After Donaghe and Townsend, 1975)

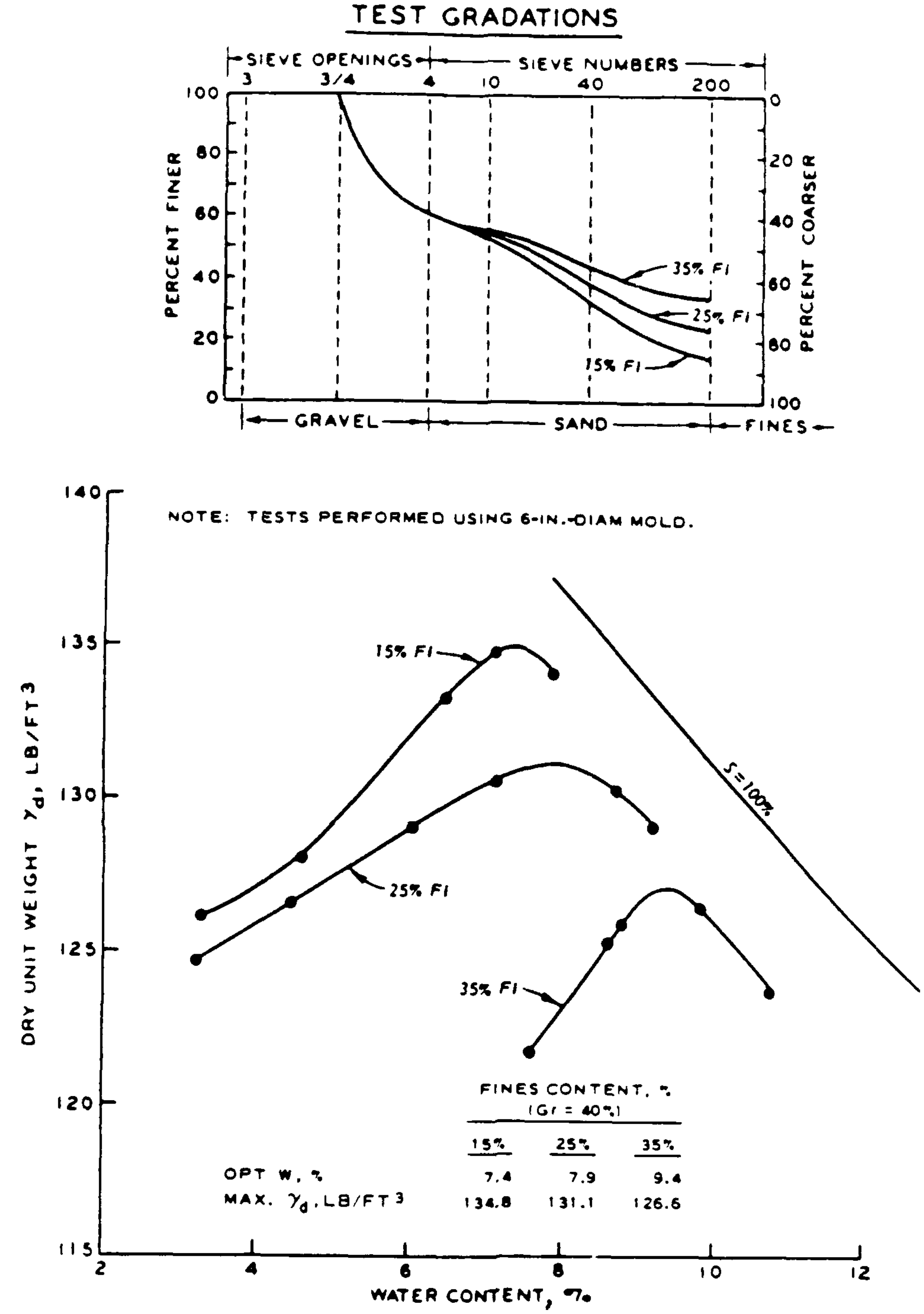


Figure 44. Compaction curves for small-scale tests conducted on specimens having scalped and replaced coarse particles with variable fines content (After Donaghe and Townsend, 1975)

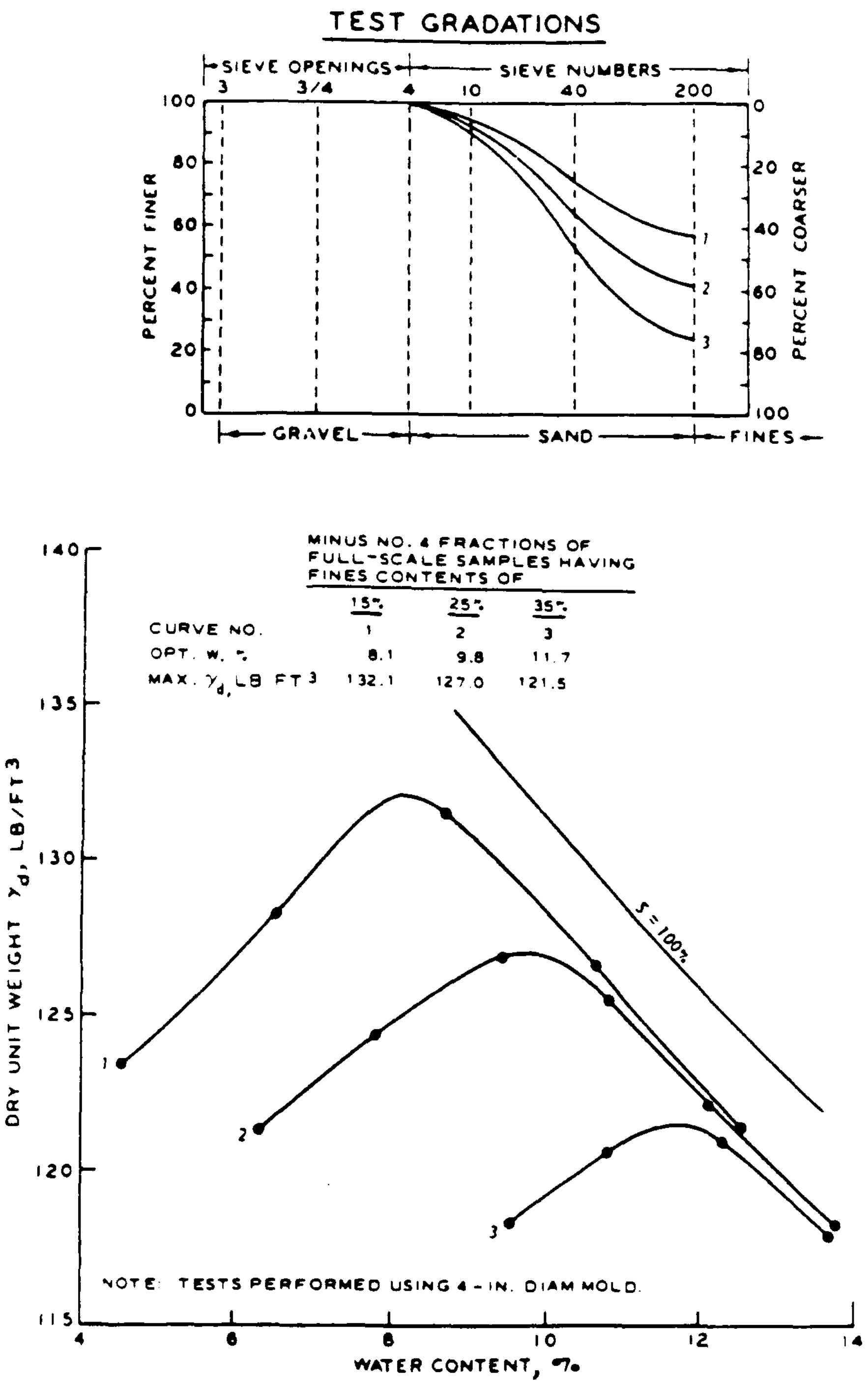


Figure 45. Compaction curves for tests conducted on minus No.4 fractions of full-scale sample series in which fines content was varied; hand-held rammer (After Donaghe and Townsend, 1975)

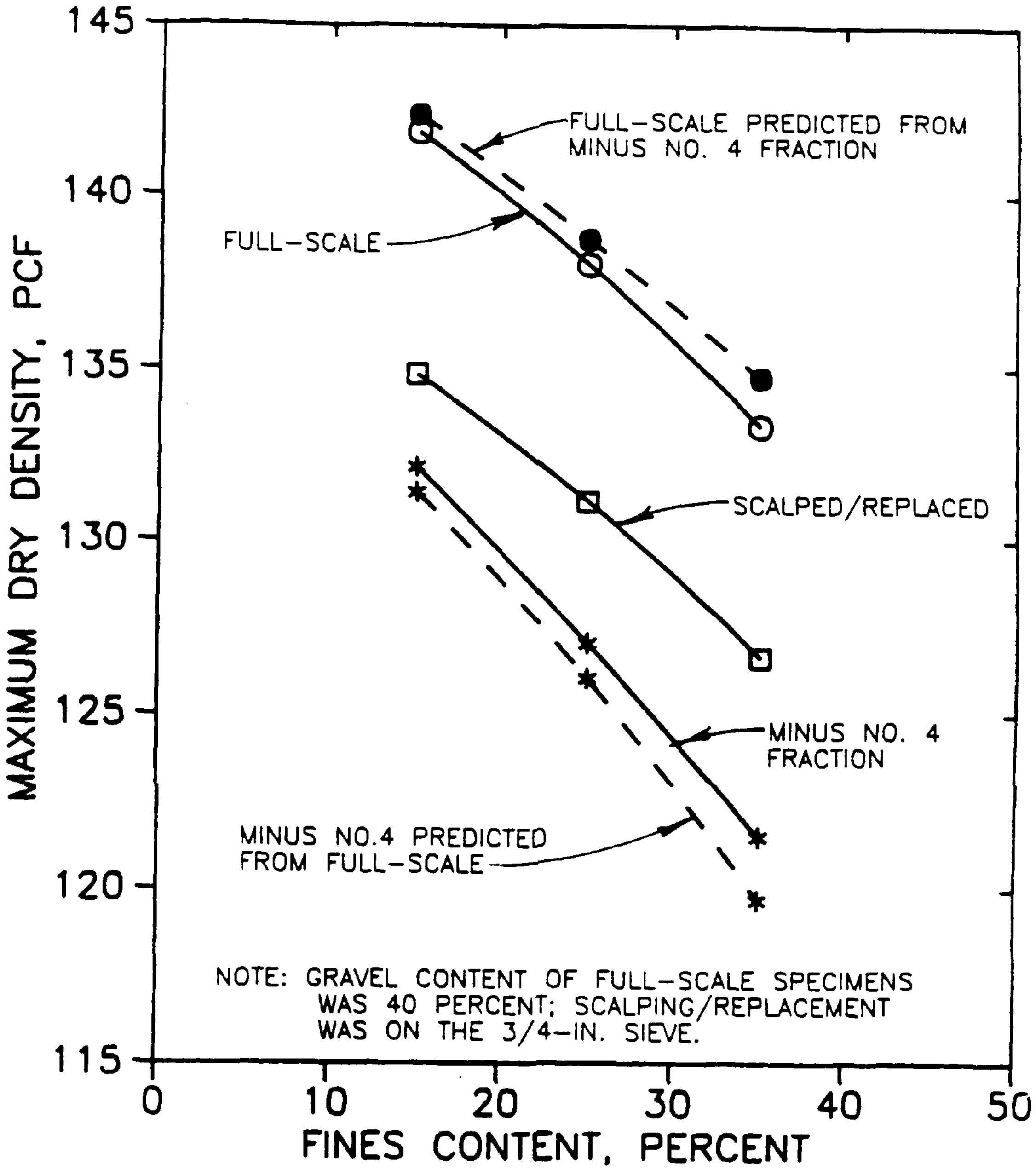


Figure 46. **Experimental and theoretical relationships between maximum dry unit weight and fines content (After Donaghe and Townsend, 1975)**

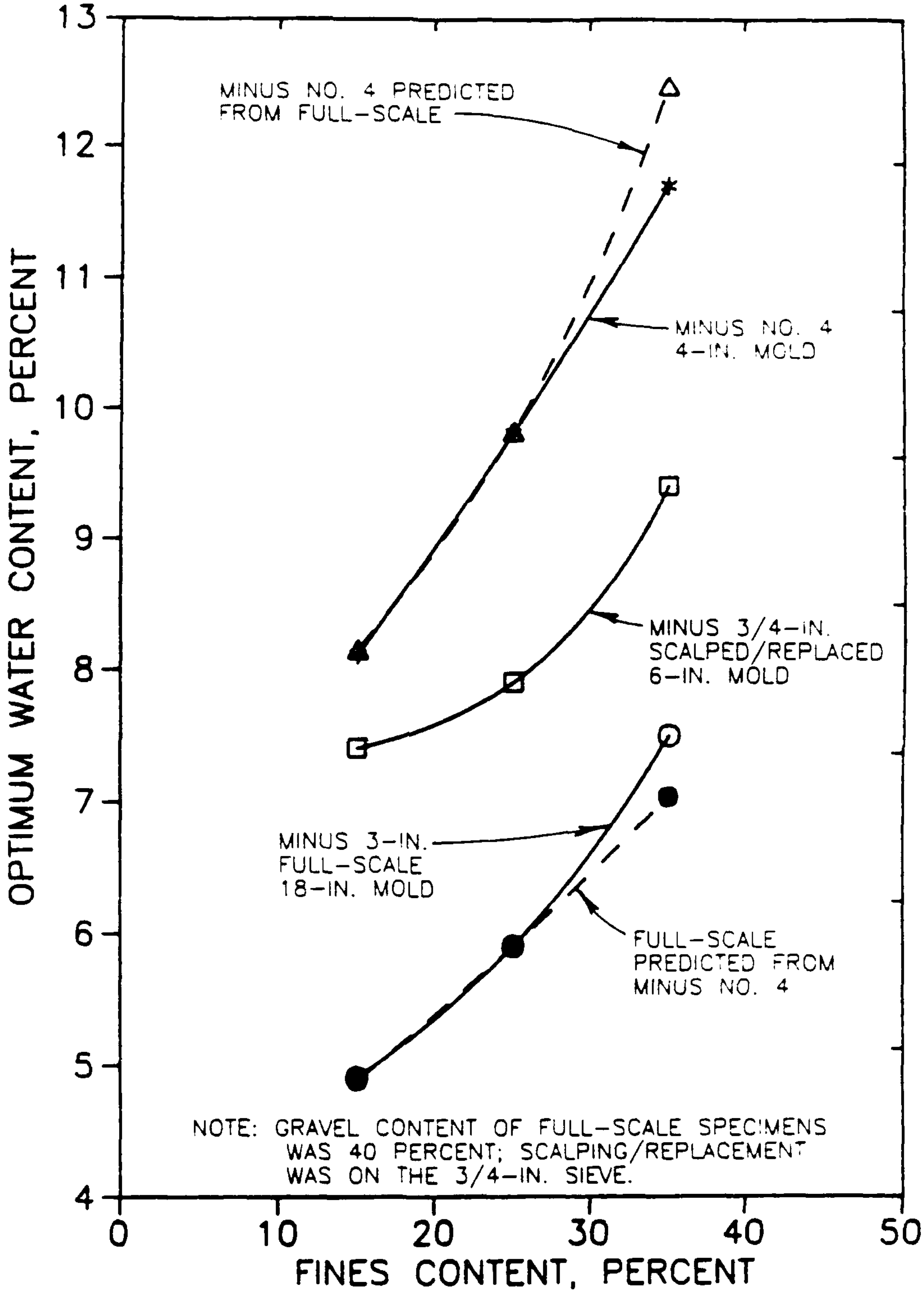


Figure 47. Experimental and theoretical relationships between optimum water content and fines content (Data from Donaghe and Townsend, 1975)

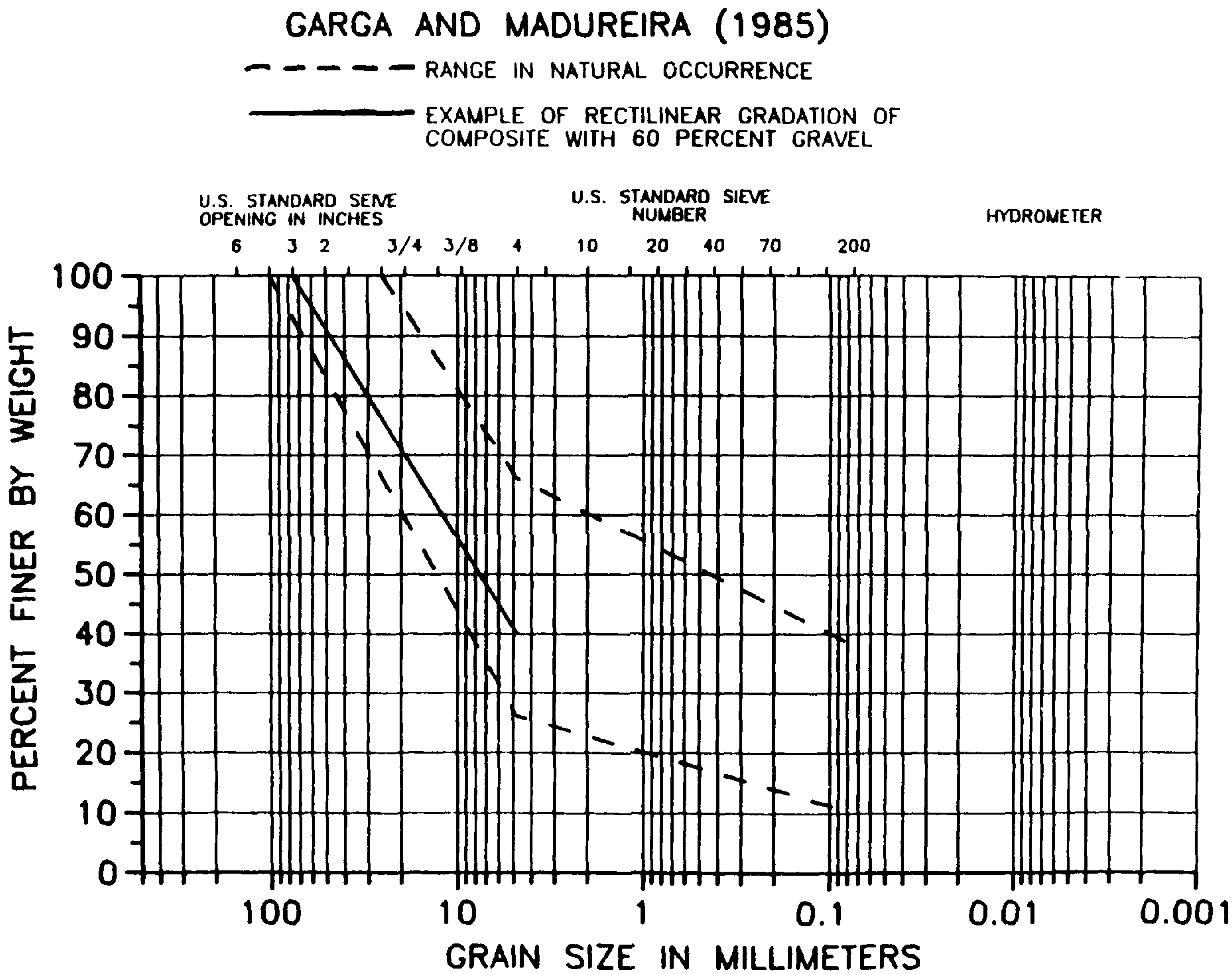


Figure 48. Grain-size distribution (After Garga and Madureira, 1985)

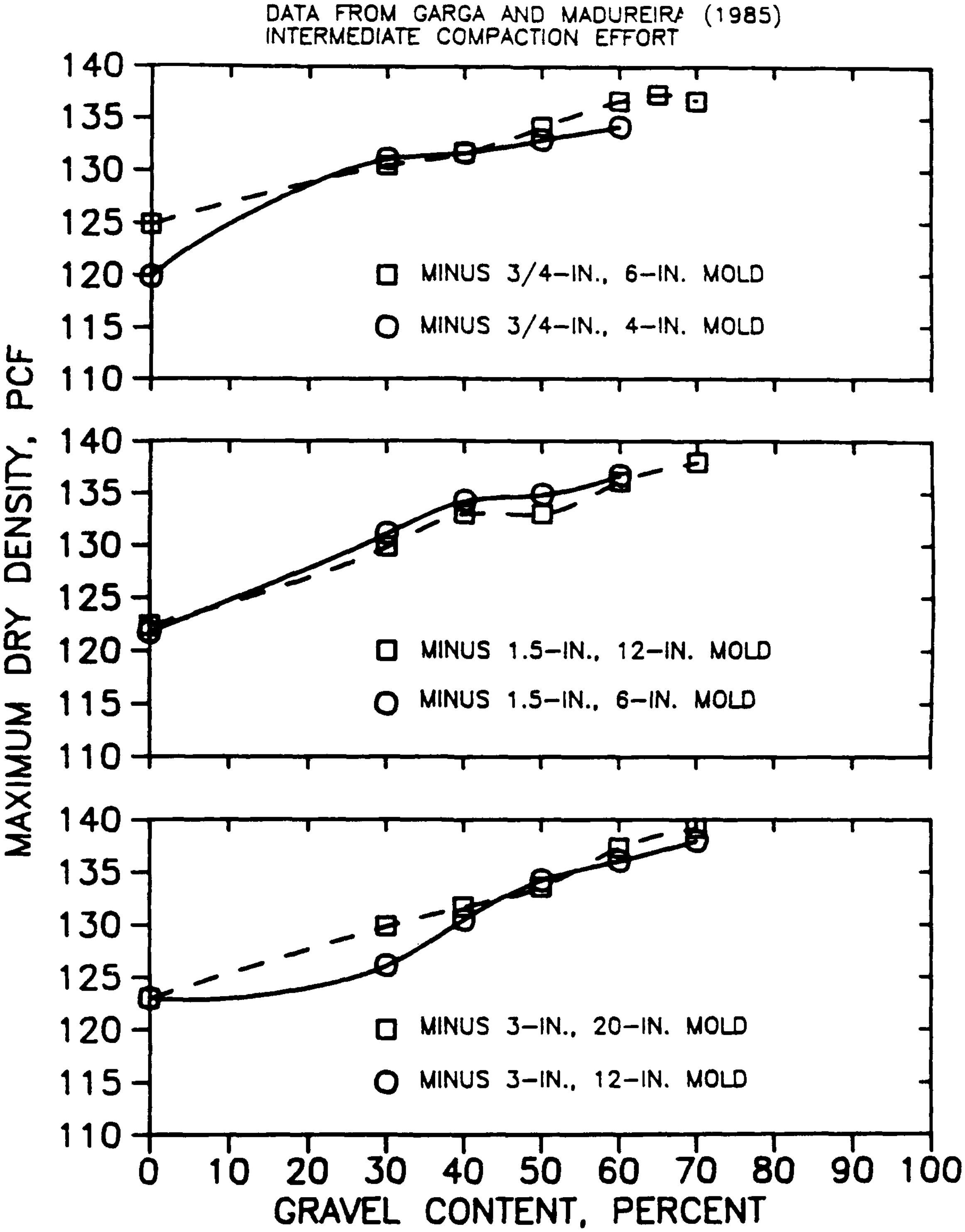


Figure 49. Influence of equipment size on maximum dry density at a compaction effort between standard and modified (Data from Garga and Madureira, 1985)

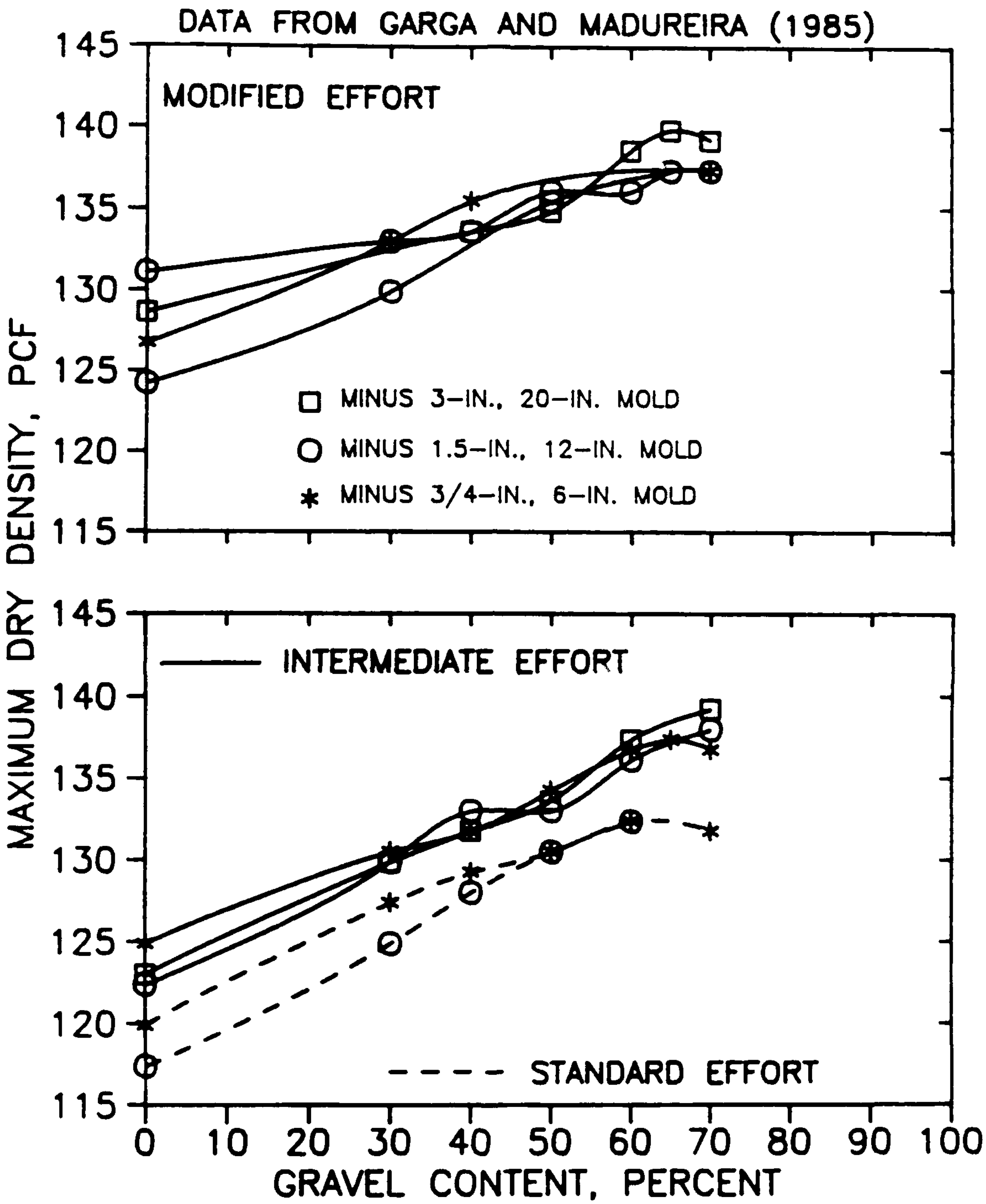


Figure 50. Influence of equipment size on maximum dry density at standard, intermediate and modified compaction efforts (Data from Garga and Madureira, 1985)

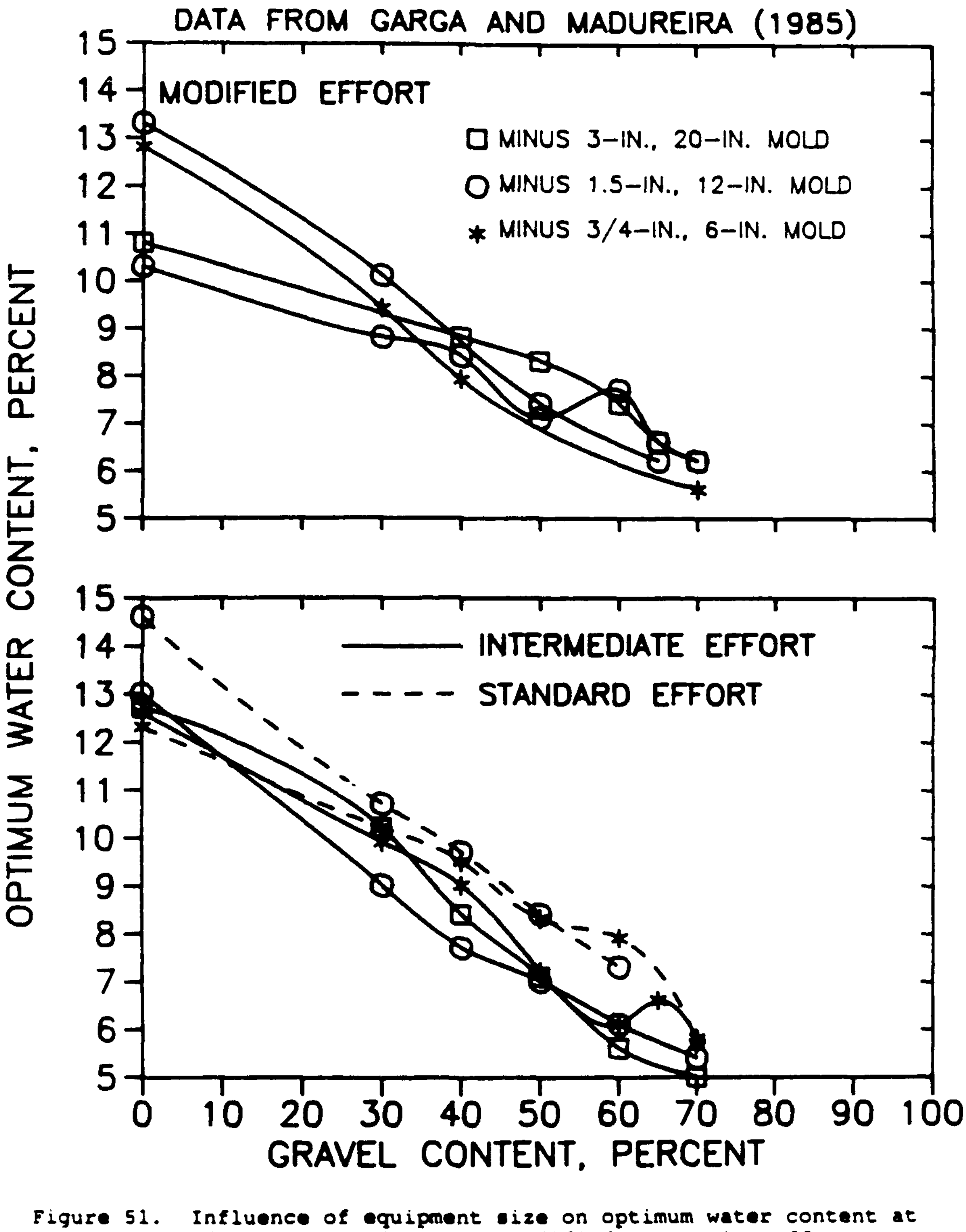


Figure 51. Influence of equipment size on optimum water content at standard, intermediate and modified compaction efforts (Data from Garga and Madureira, 1985

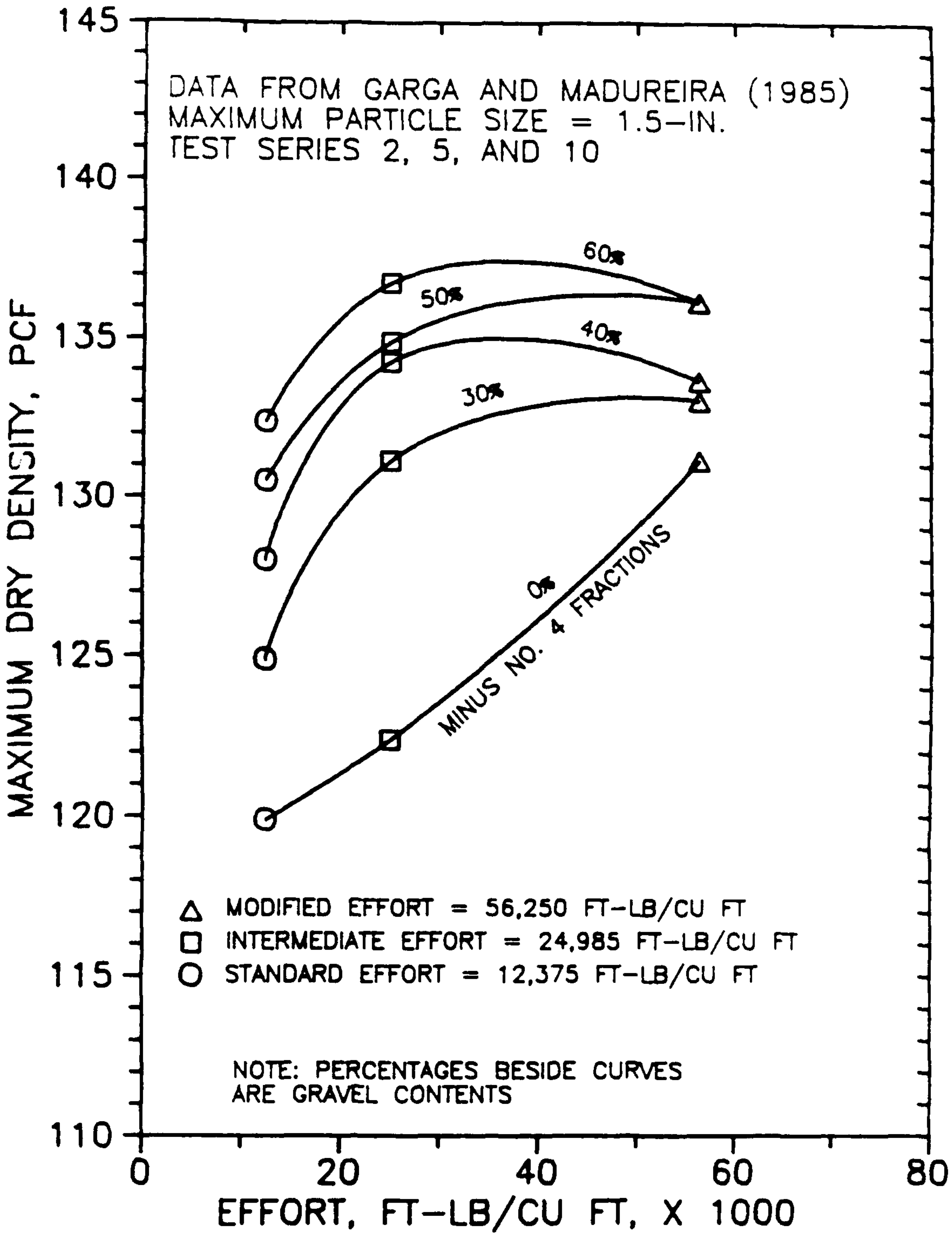


Figure 52. Maximum dry density versus compactive effort and gravel content (Data from Garga and Madureira, 1985)

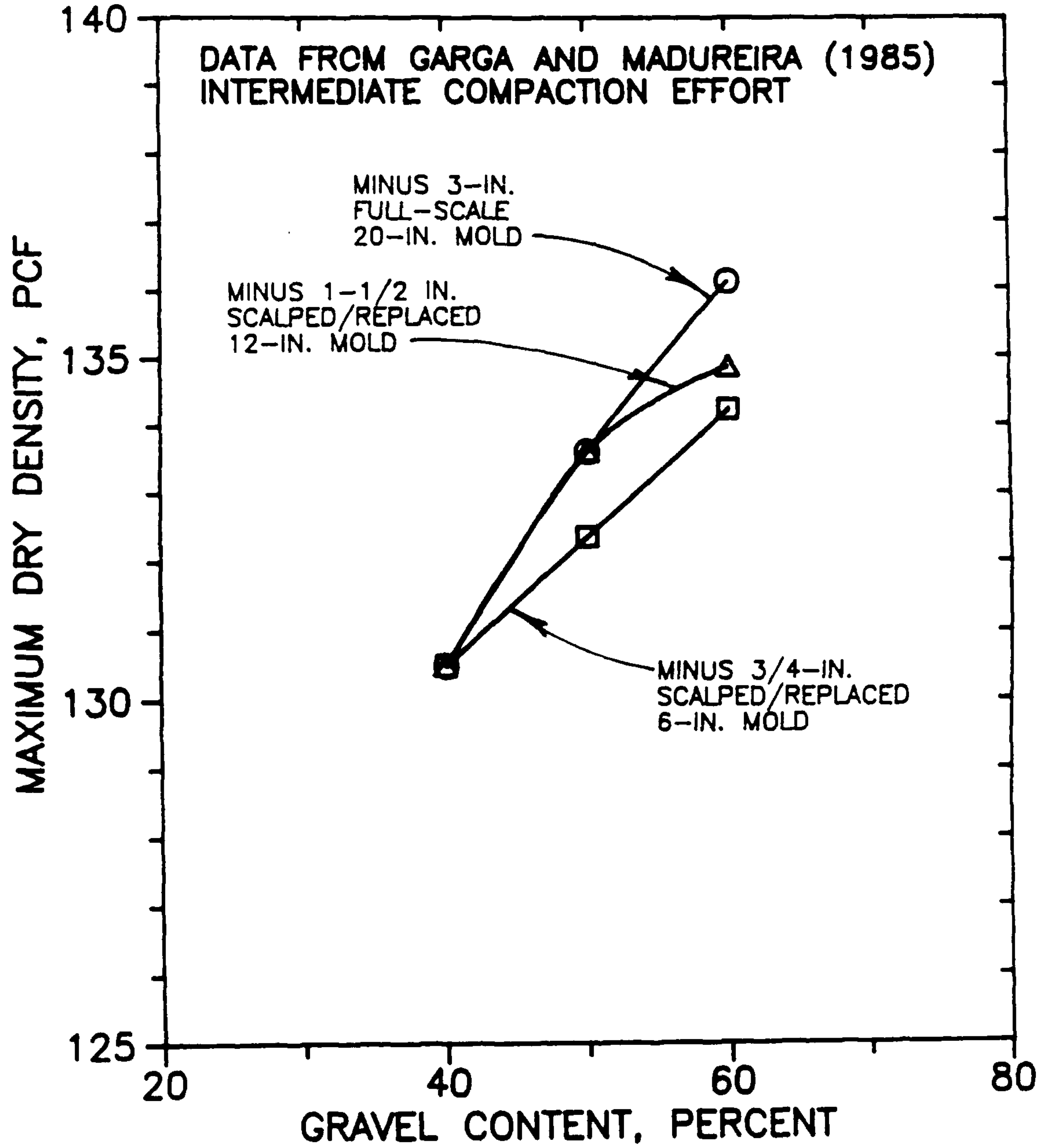


Figure 53. Comparisons of maximum dry densities from full-scale and scalped/replaced gradations (Data from Garga and Madureira, 1985)

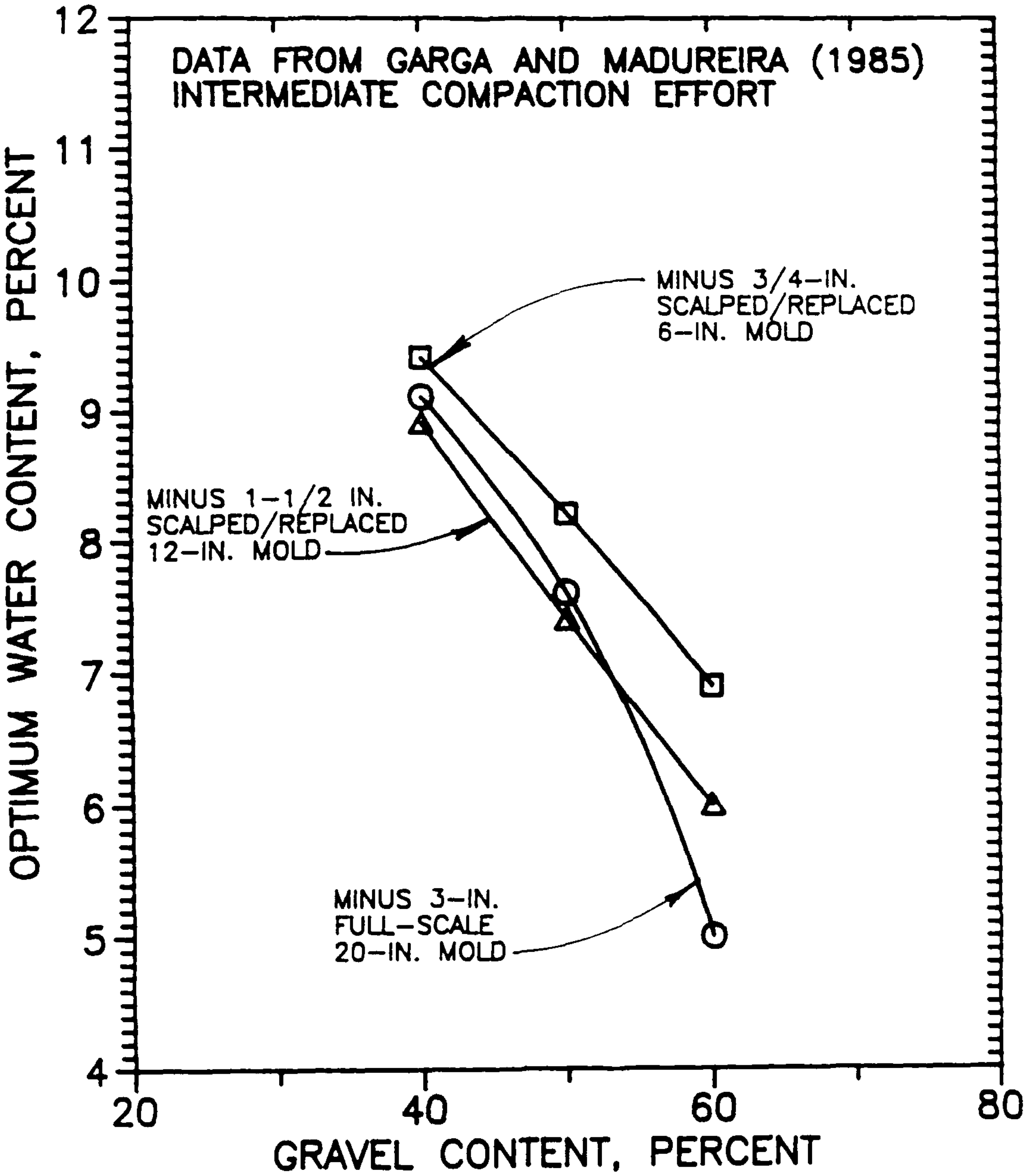


Figure 54. Comparisons of optimum water contents from full-scale and scalped/replaced gradations (Data from Garga and Madureira, 1985)

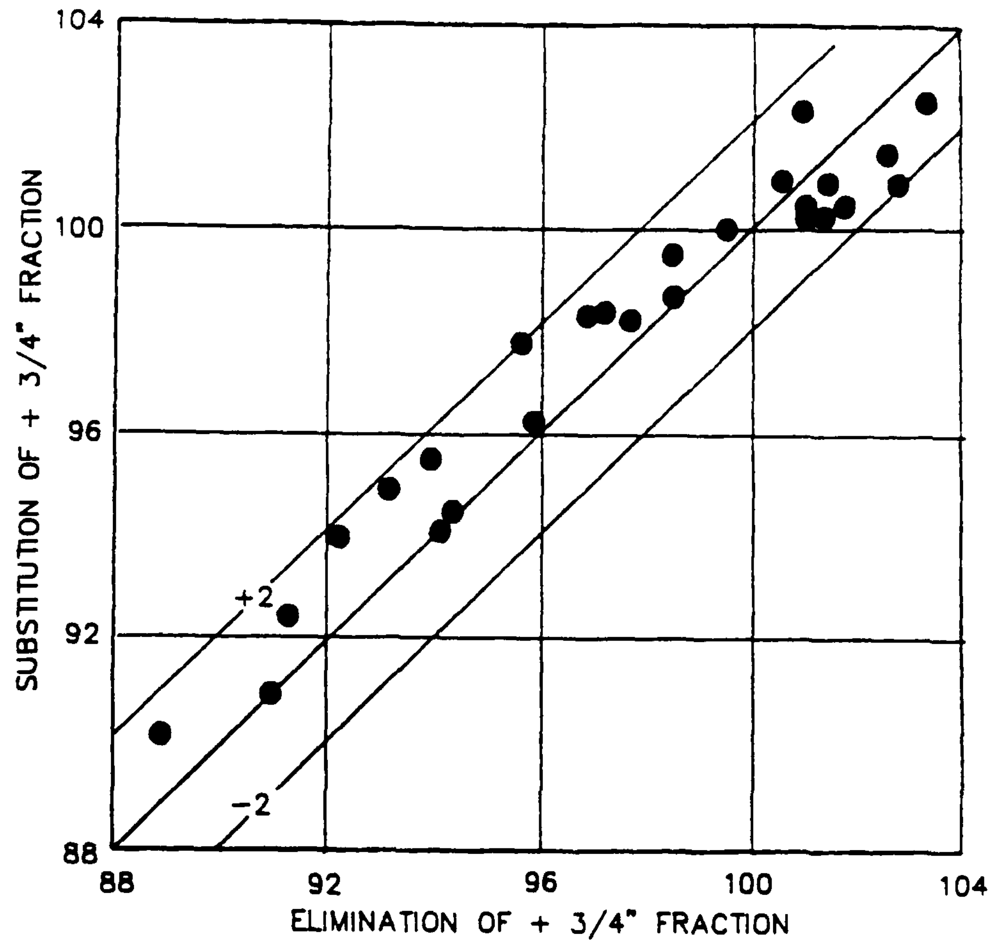


Figure 55. Comparison of degree of compaction from two methods (After Garga and Madureira, 1985)

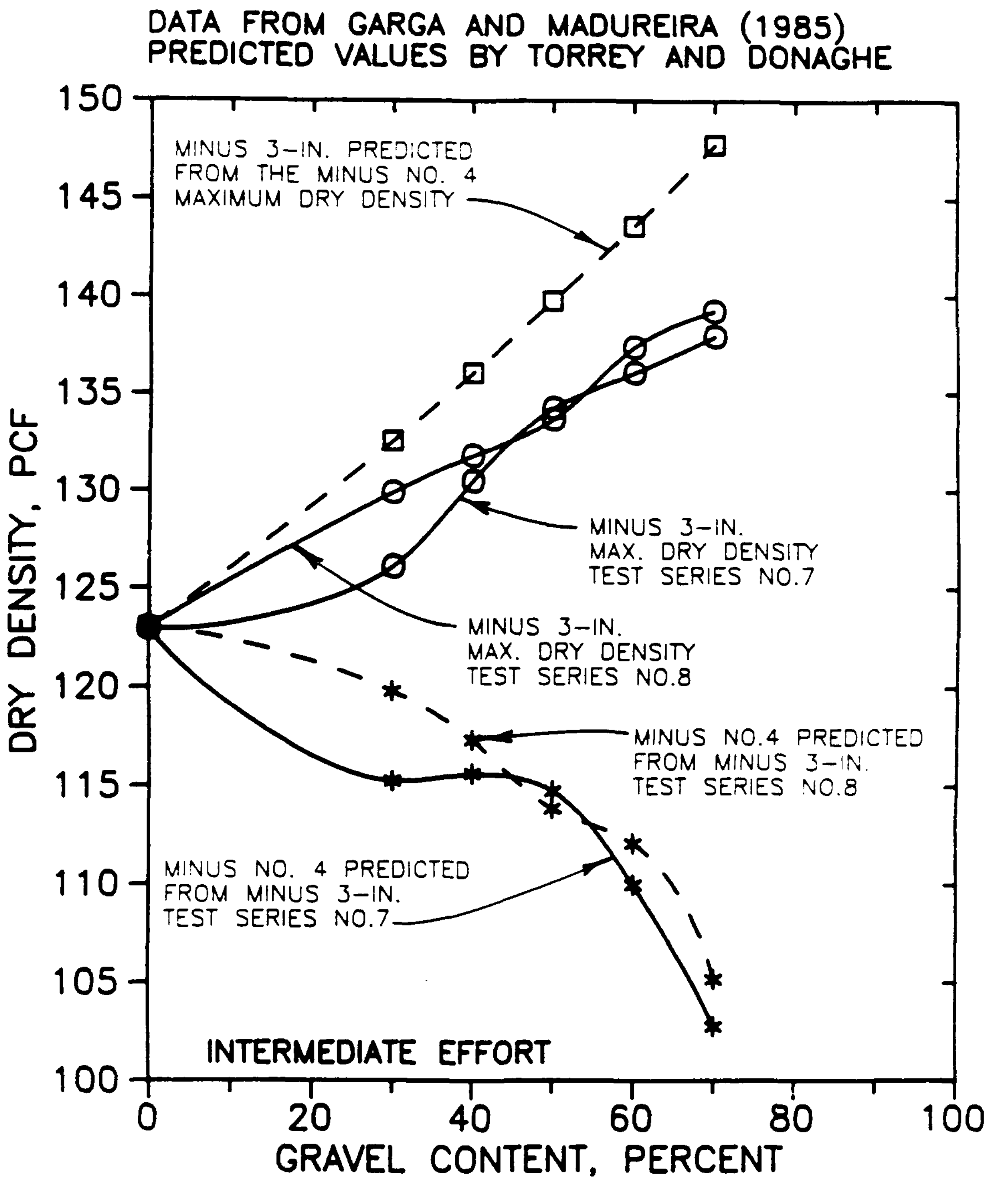


Figure 56. Experimental and theoretical relationships between intermediate effort maximum dry density and gravel content, minus 3-in. gradation (data from Garga and Madureira, 1985)

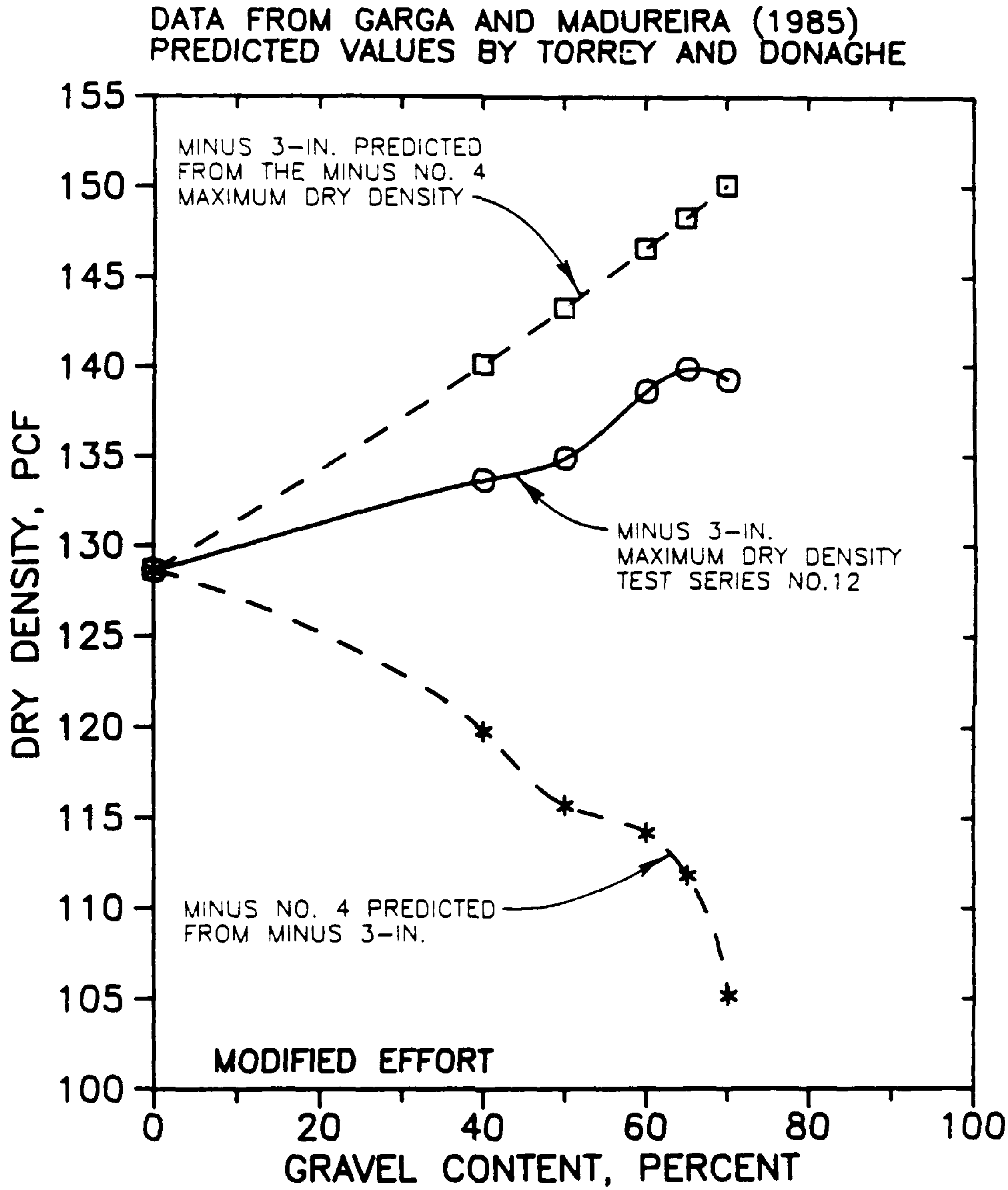


Figure 57. Experimental and theoretical relationships between modified effort dry density and gravel content, minus 3-in. gradation (data from Garga and Madureira, 1985)

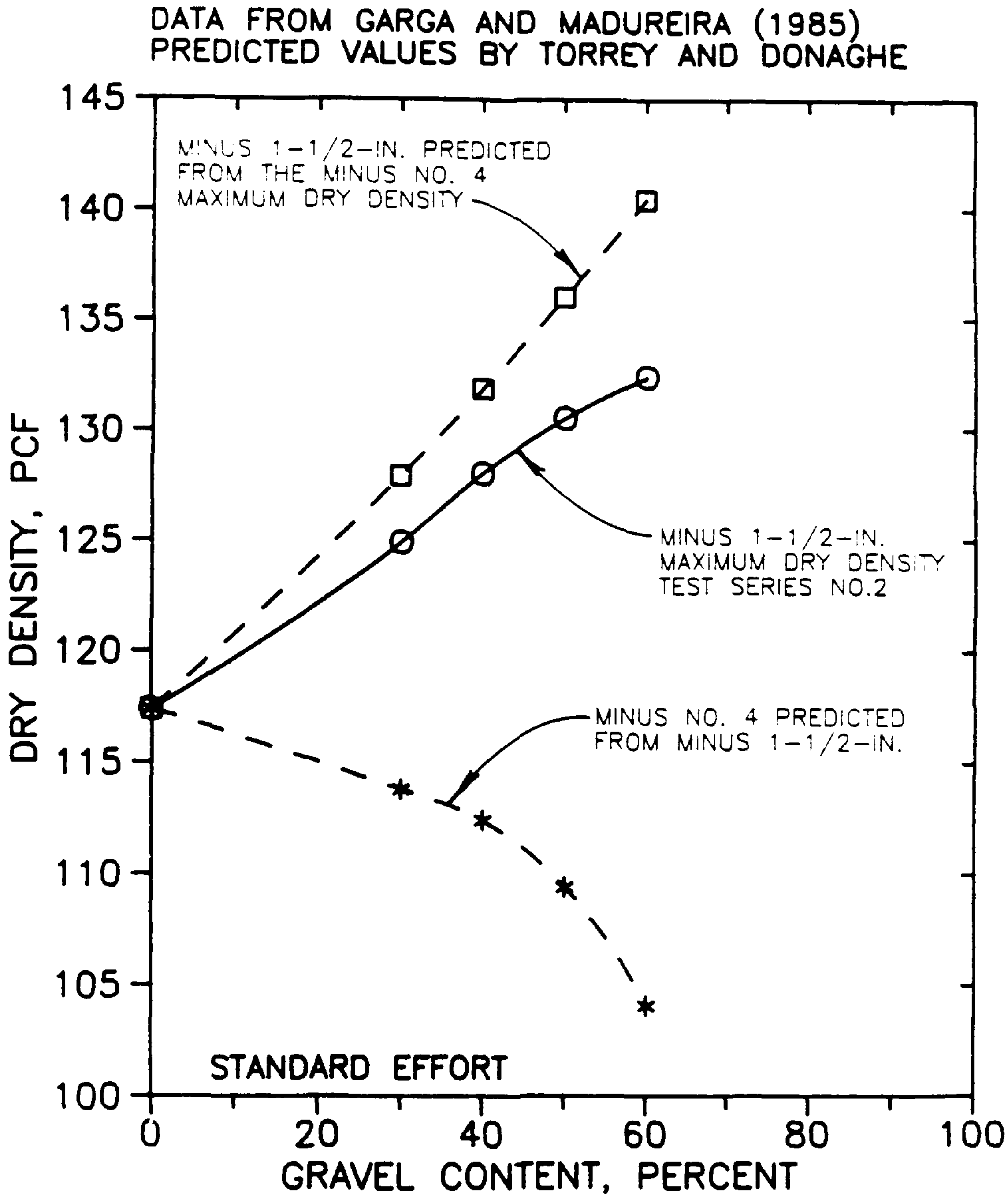


Figure 58. Experimental and theoretical relationships between standard effort dry density and gravel content, minus 1-1/2-in. gradation (data from Garga and Madureira, 1985)

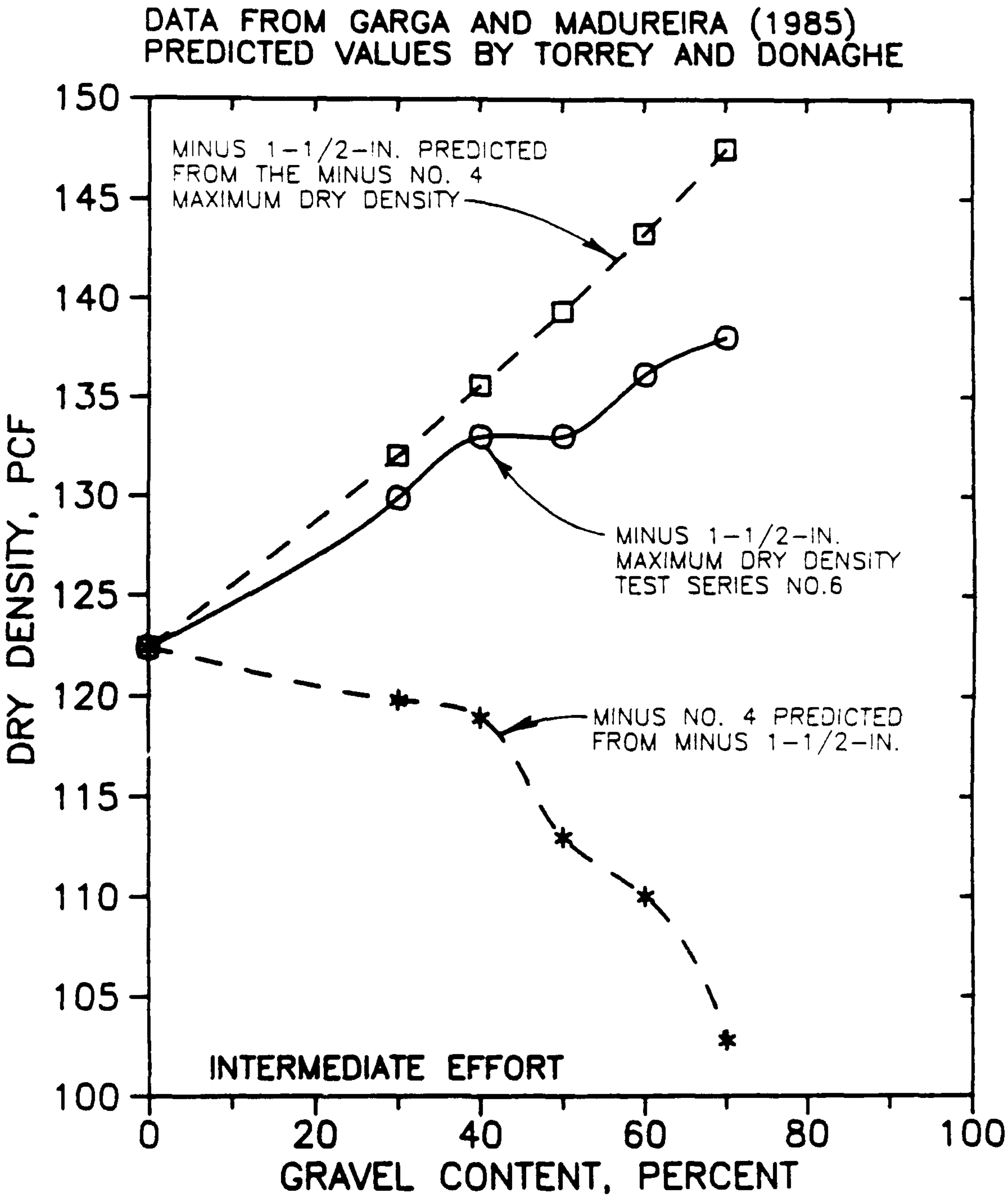


Figure 59. Experimental and theoretical relationships between intermediate effort dry density and gravel content, minus 1-1/2-in. gradation (data from Garga and Madureira, 1985)

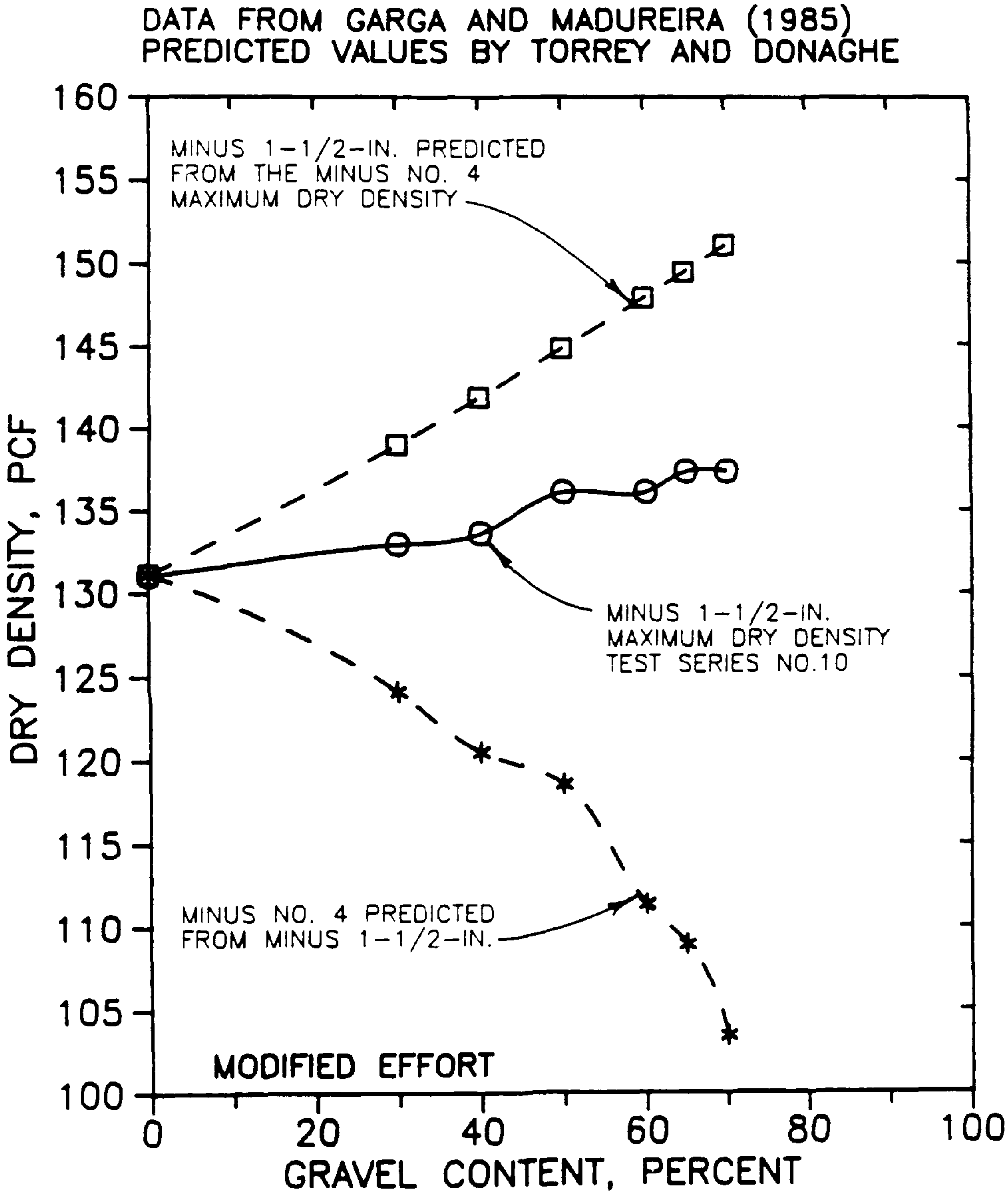


Figure 60. Experimental and theoretical relationships between modified effort dry density and gravel content, minus 1-1/2-in. gradation (data from Garga and Madureira, 1985)

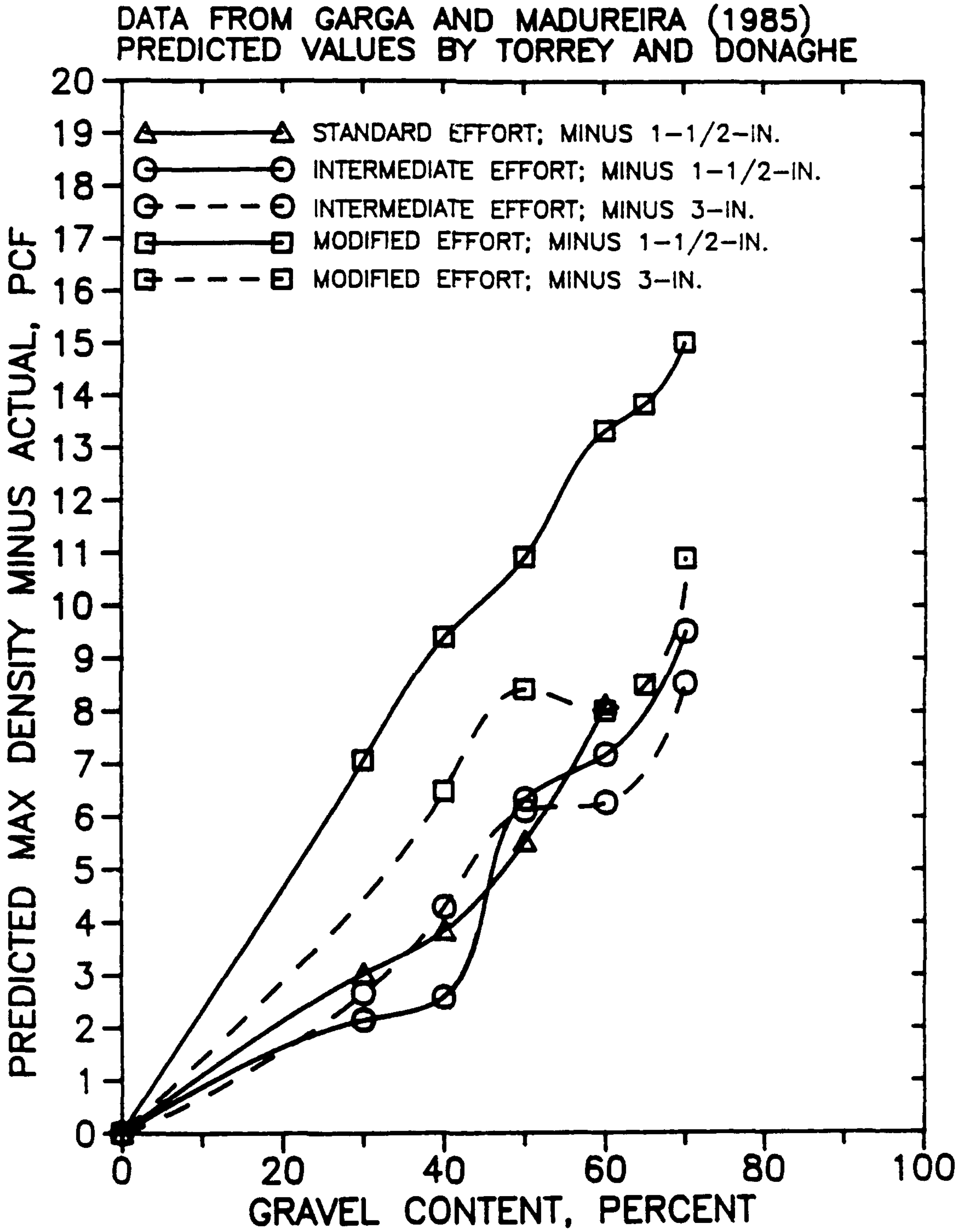


Figure 61. Predicted values of maximum dry density minus actual values versus gravel content (data from Garga and Madureira, 1985)

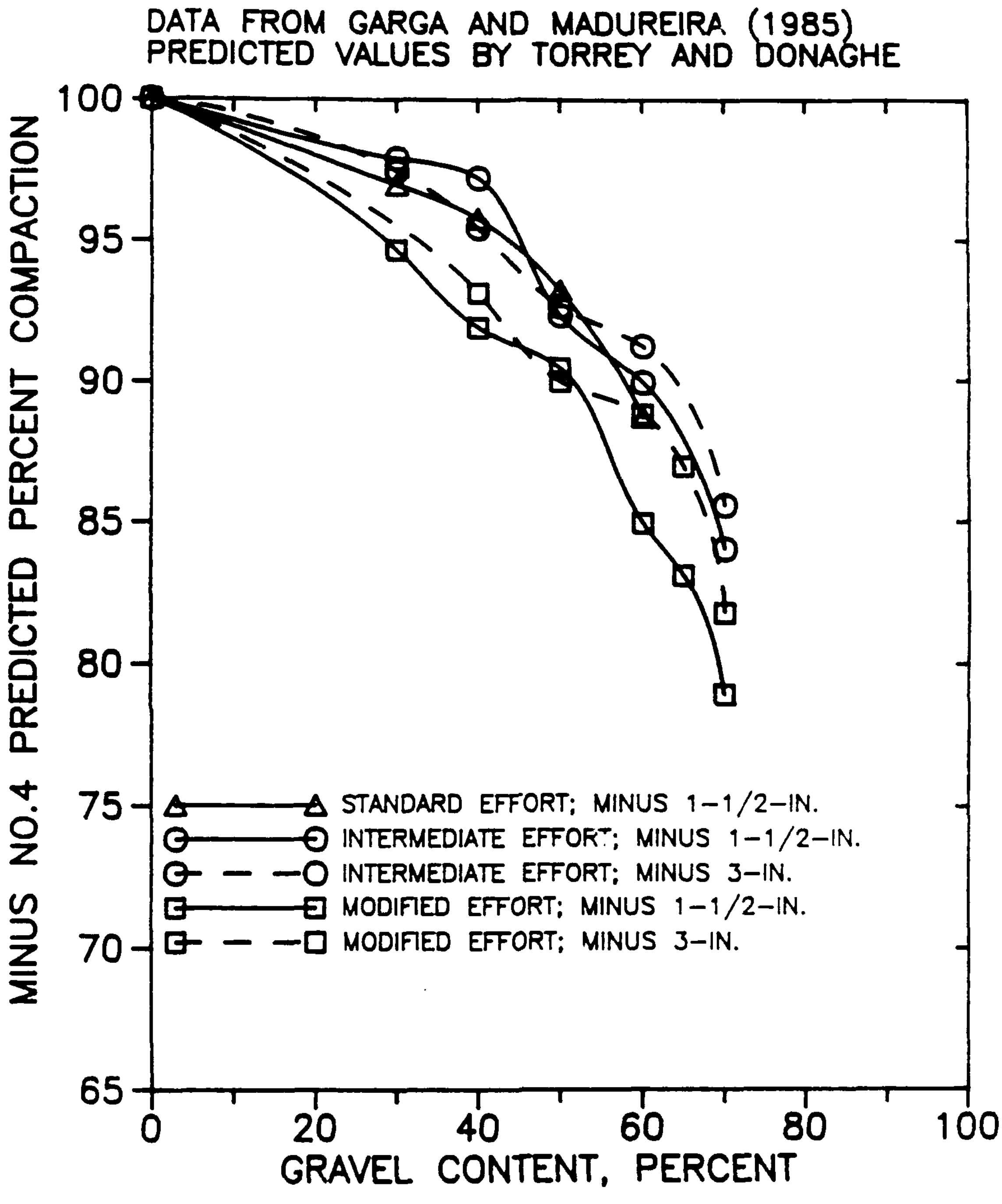


Figure 62. Predicted percent compaction of minus No.4 fractions versus gravel content (data from Garga and Madureira, 1985)

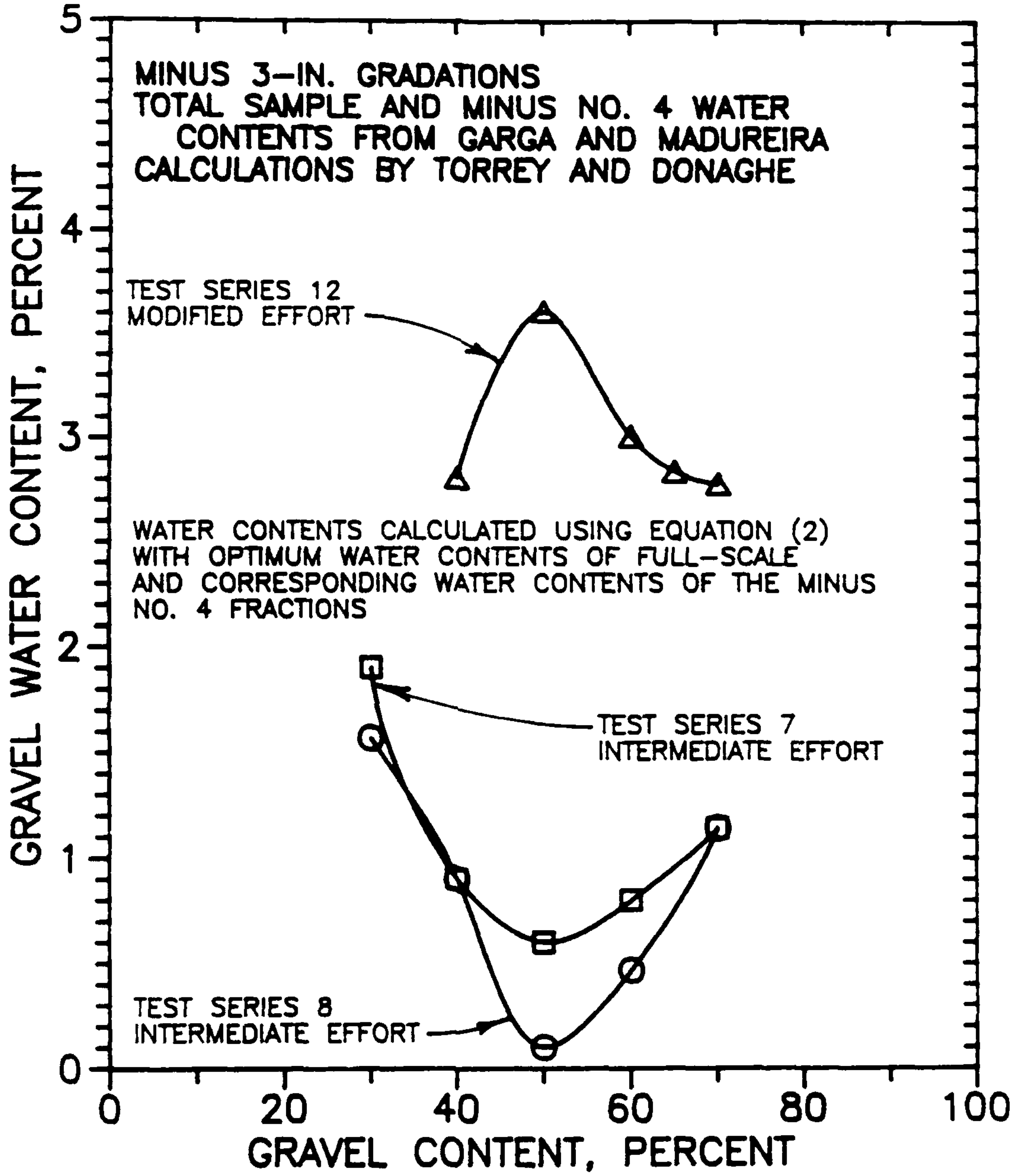


Figure 63. Gravel water content versus gravel content, minus 3-in. gradations (data from Garga and Madureira, 1985)

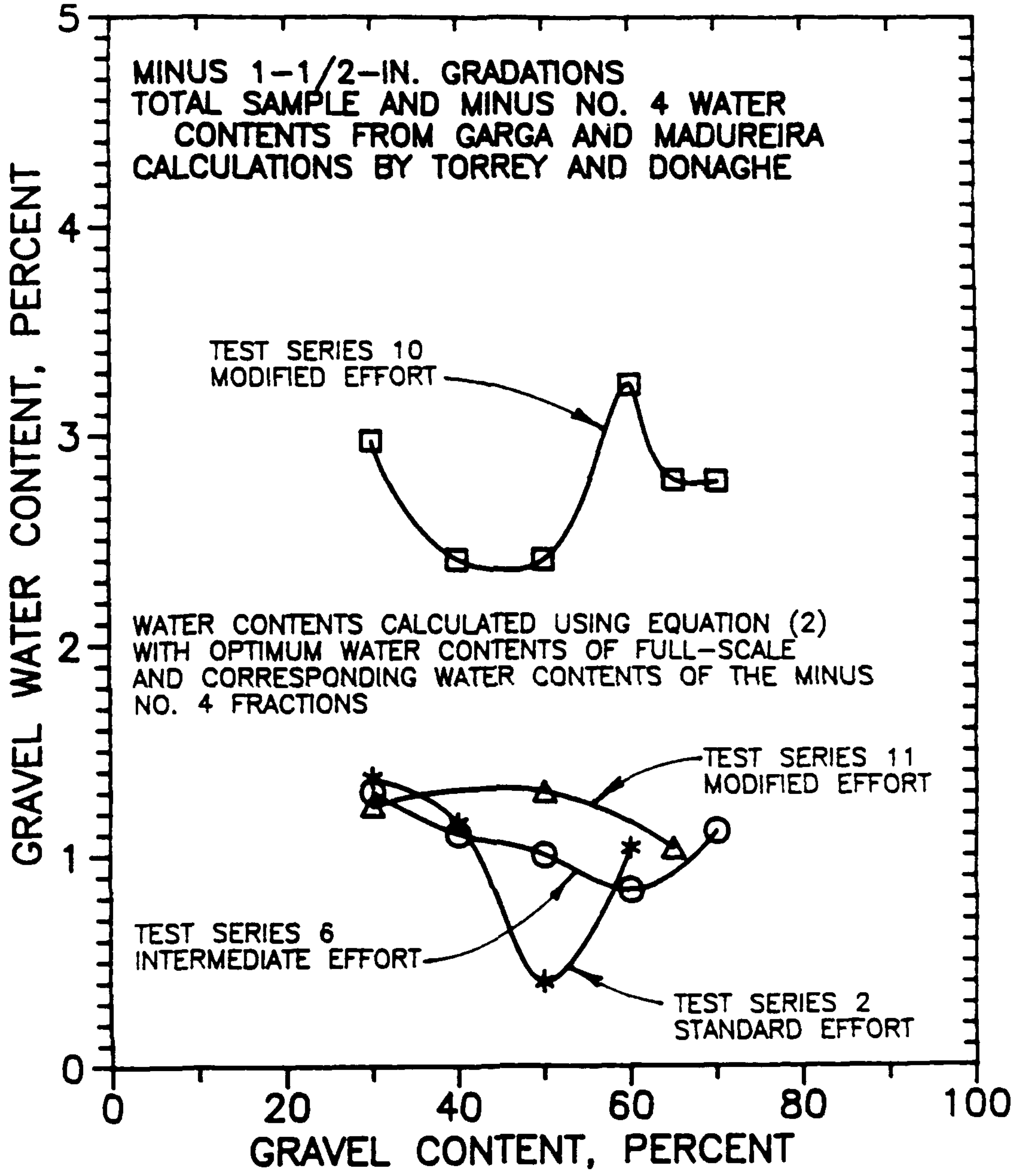


Figure 64. Gravel water content versus gravel content, minus 1-1/2-in. gradations (data from Garga and Madureira, 1985)

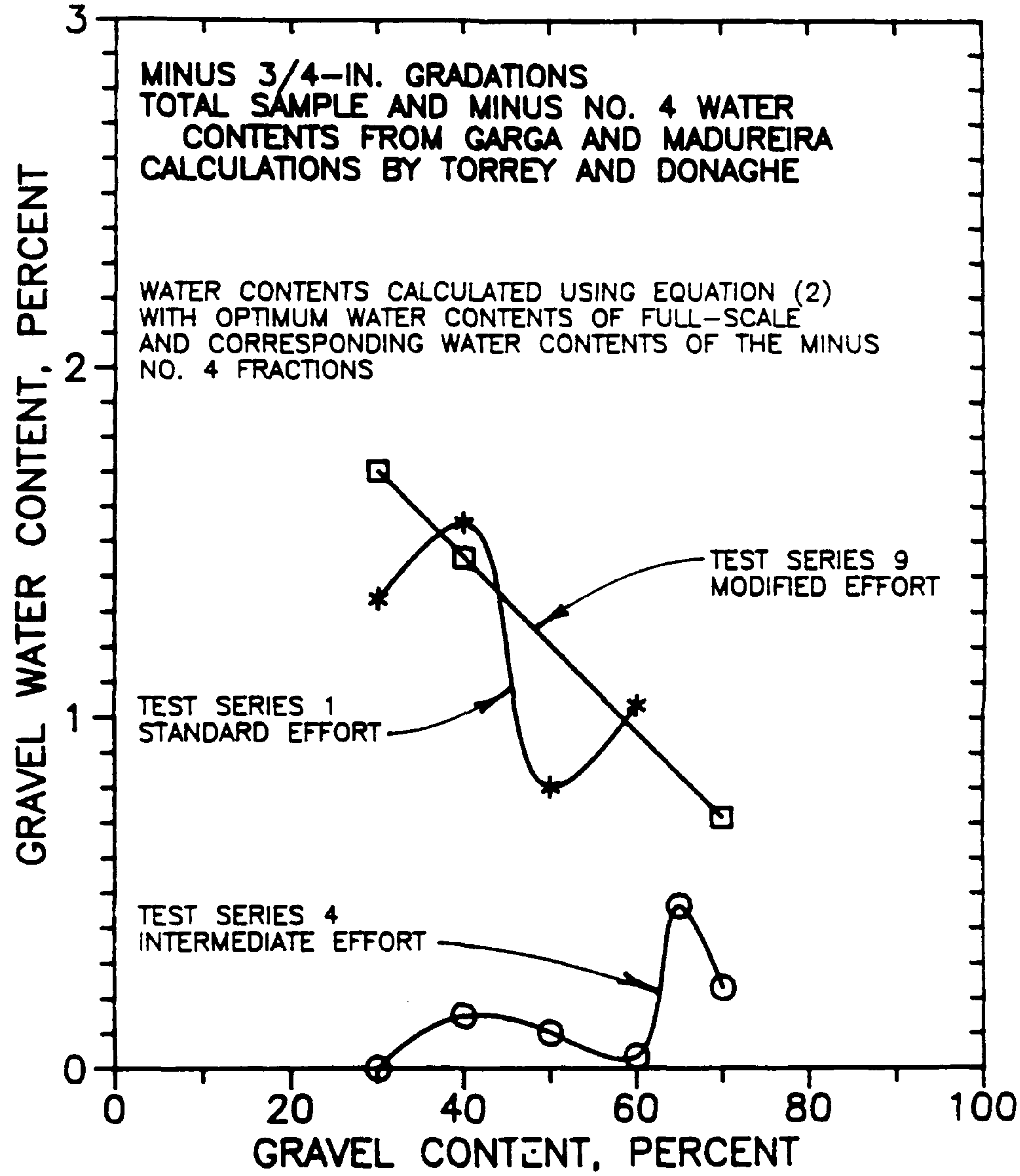


Figure 65. Gravel water content versus gravel content, minus 3/4-in. gradation (data from Garga and Madureira, 1985)

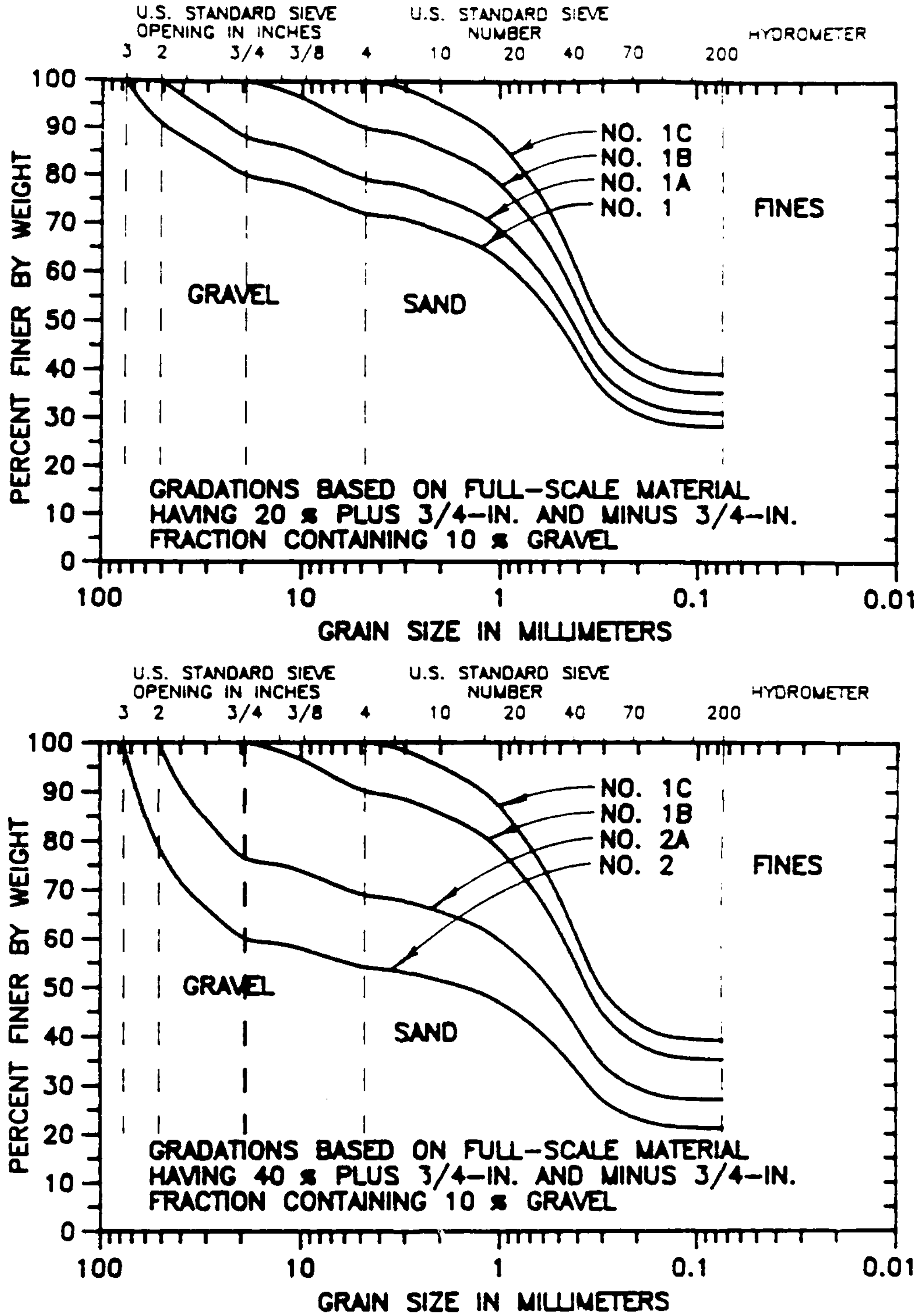


Figure 66. Grain-size distribution curves for test gradation Nos. 1 and 2 and associated fractions

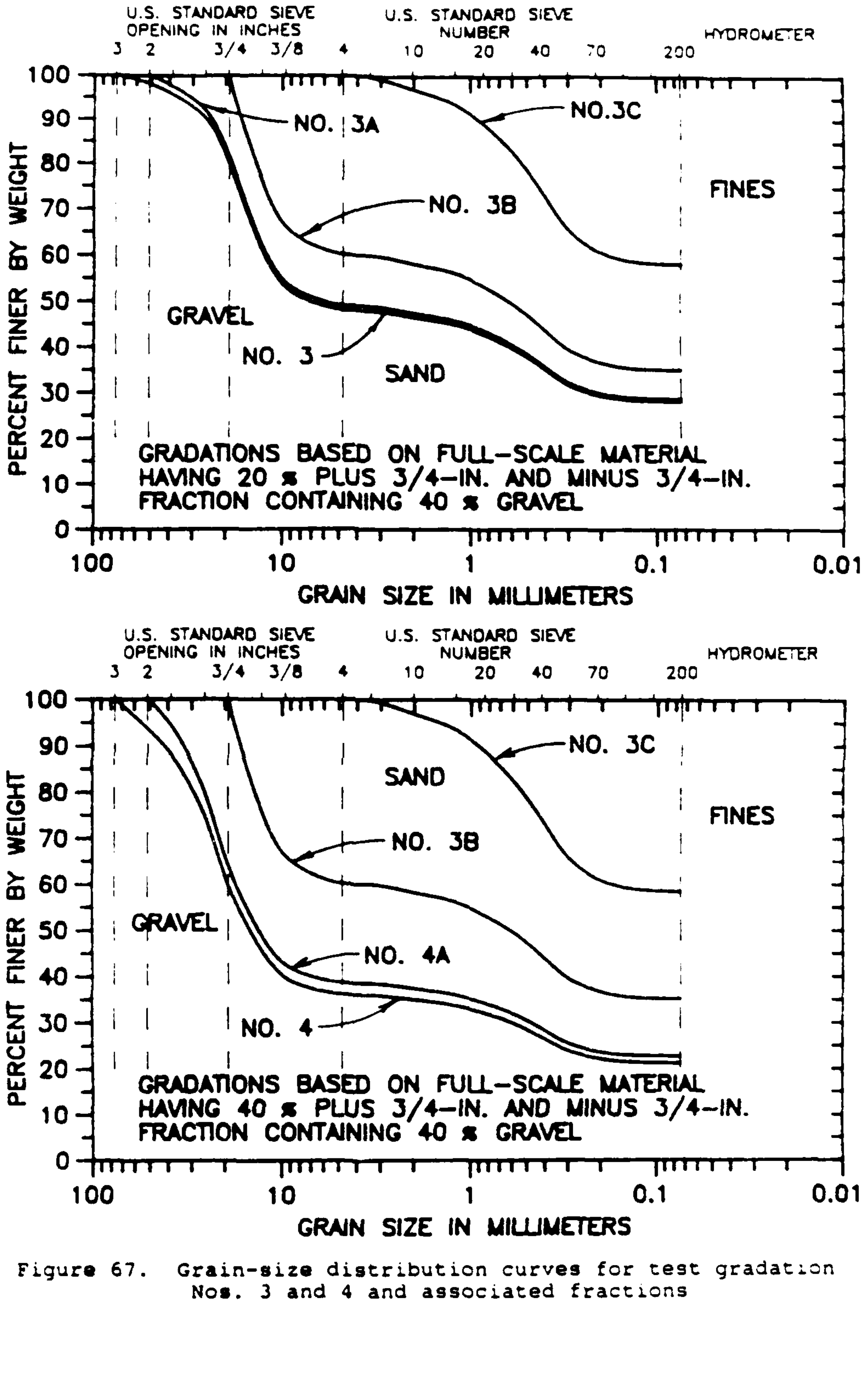
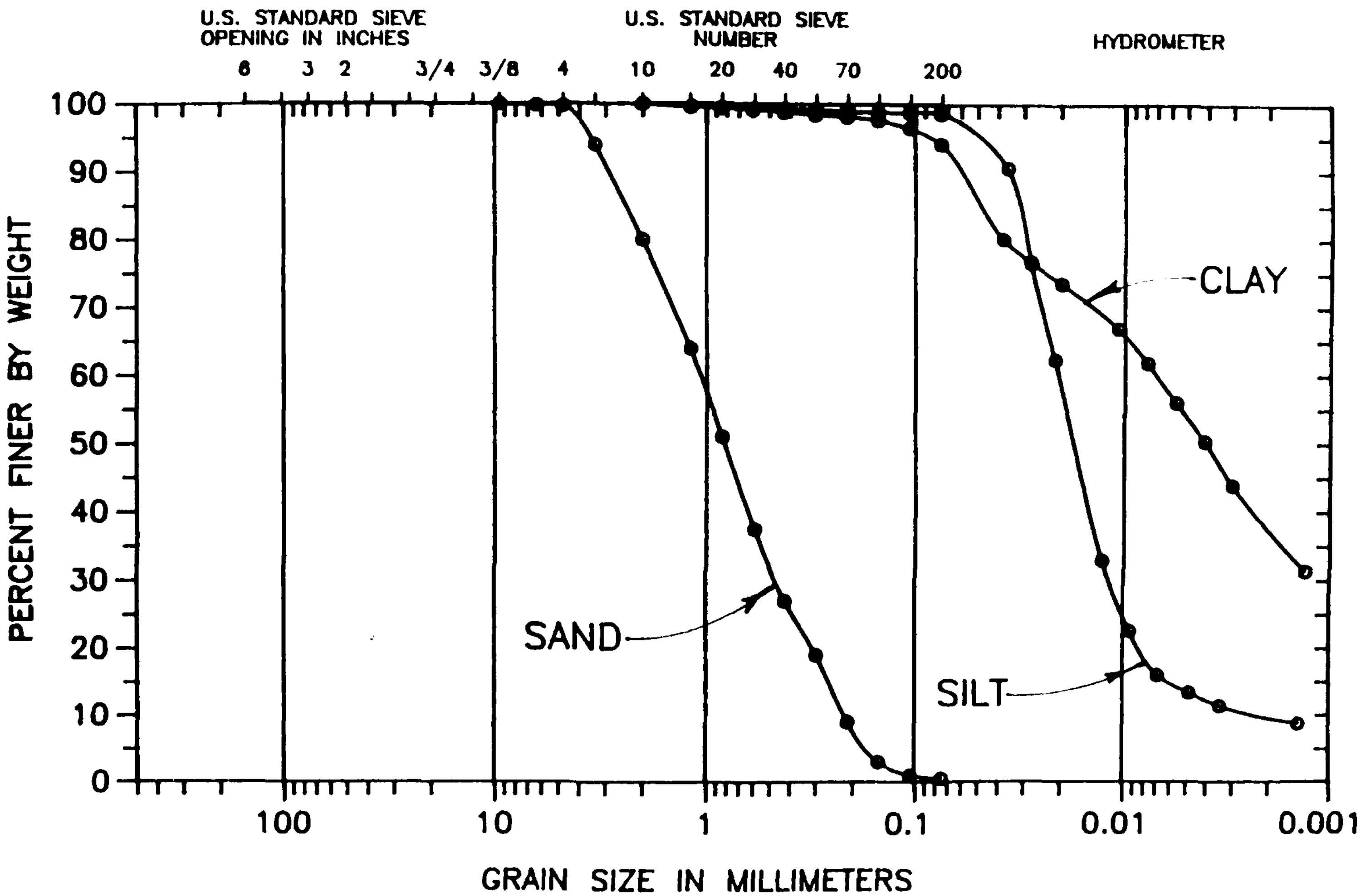


Figure 67. Grain-size distribution curves for test gradation Nos. 3 and 4 and associated fractions



CLASSIFICATION:	LL	PL	PI	G_s
CLAY (CH), BROWNISH GRAY	62	19	43	2.72
SILT (ML), BROWN	29	23	6	2.72
SAND (SP), LIGHT BROWN	NP			2.65

Figure 68. Grain-size distribution curves and classification data for sand (SP), silt (ML) and clay (CH) used in the testing program

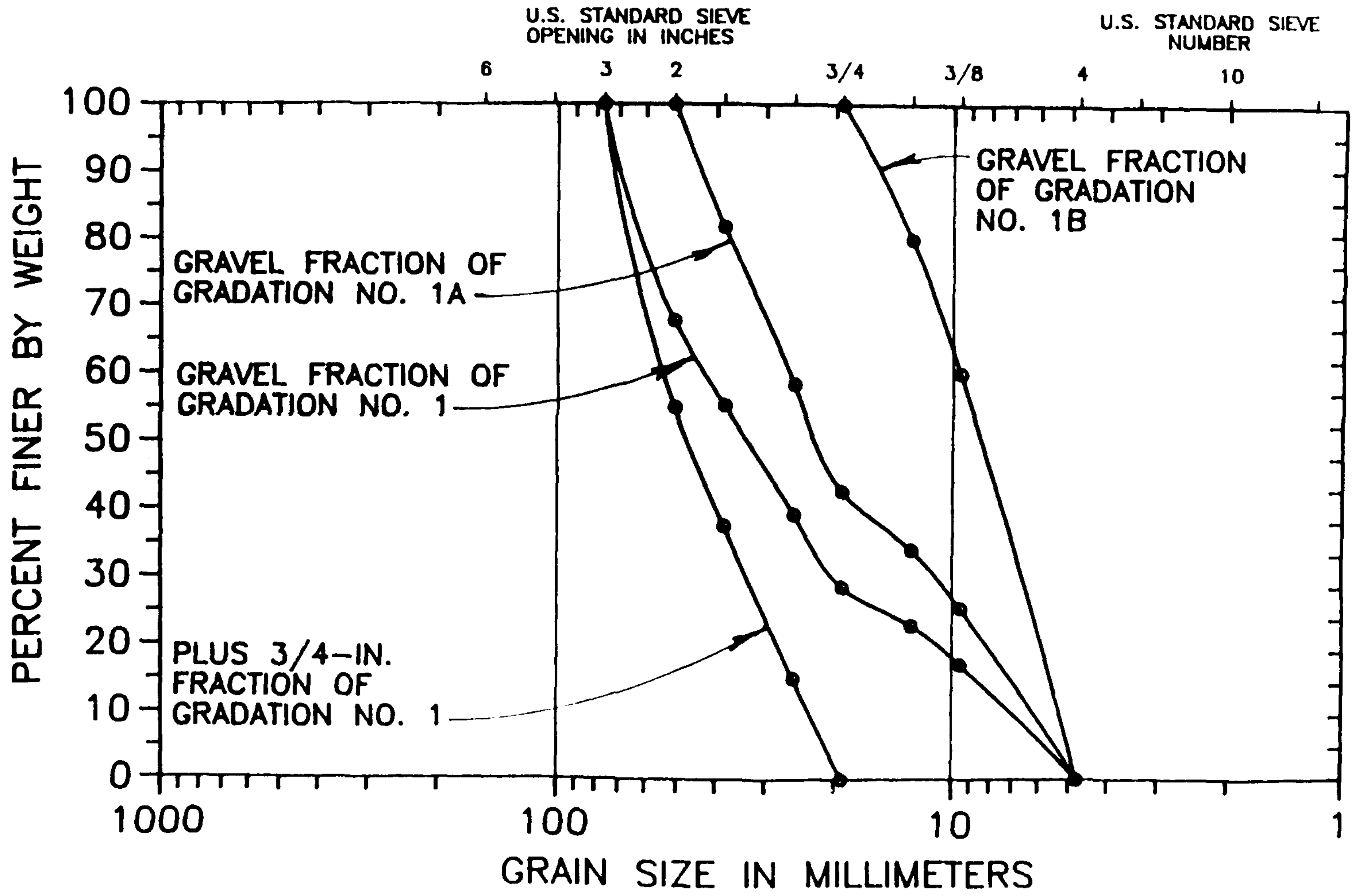


Figure 69. Grain-size distribution curves for gravel fraction of test gradation No.1, its associated fractions and its plus 3/4-in. fraction.

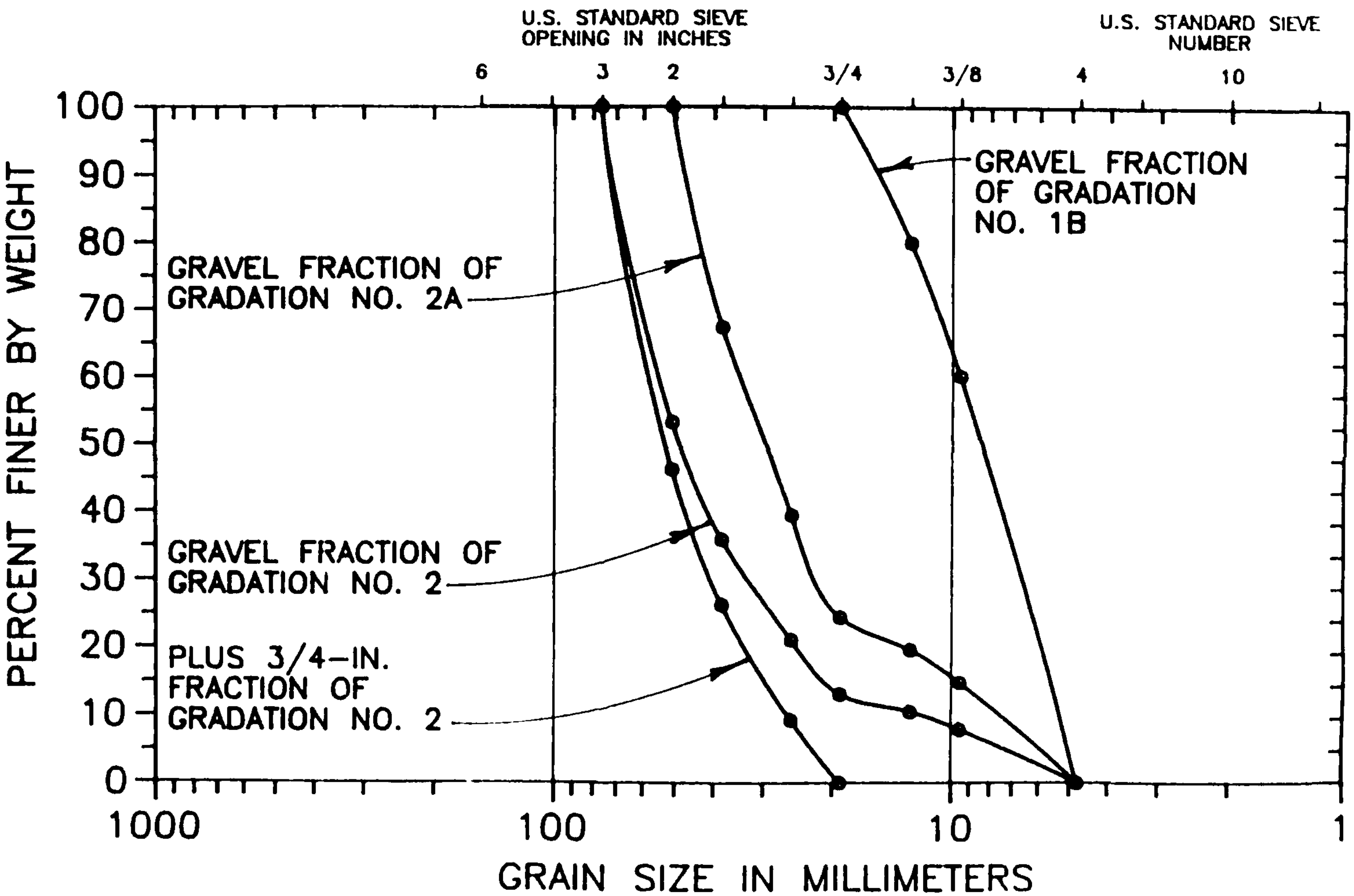


Figure 70. Grain-size distribution curves for gravel fraction of test gradation No.2, its associated fractions and its plus 3/4-in. fraction.

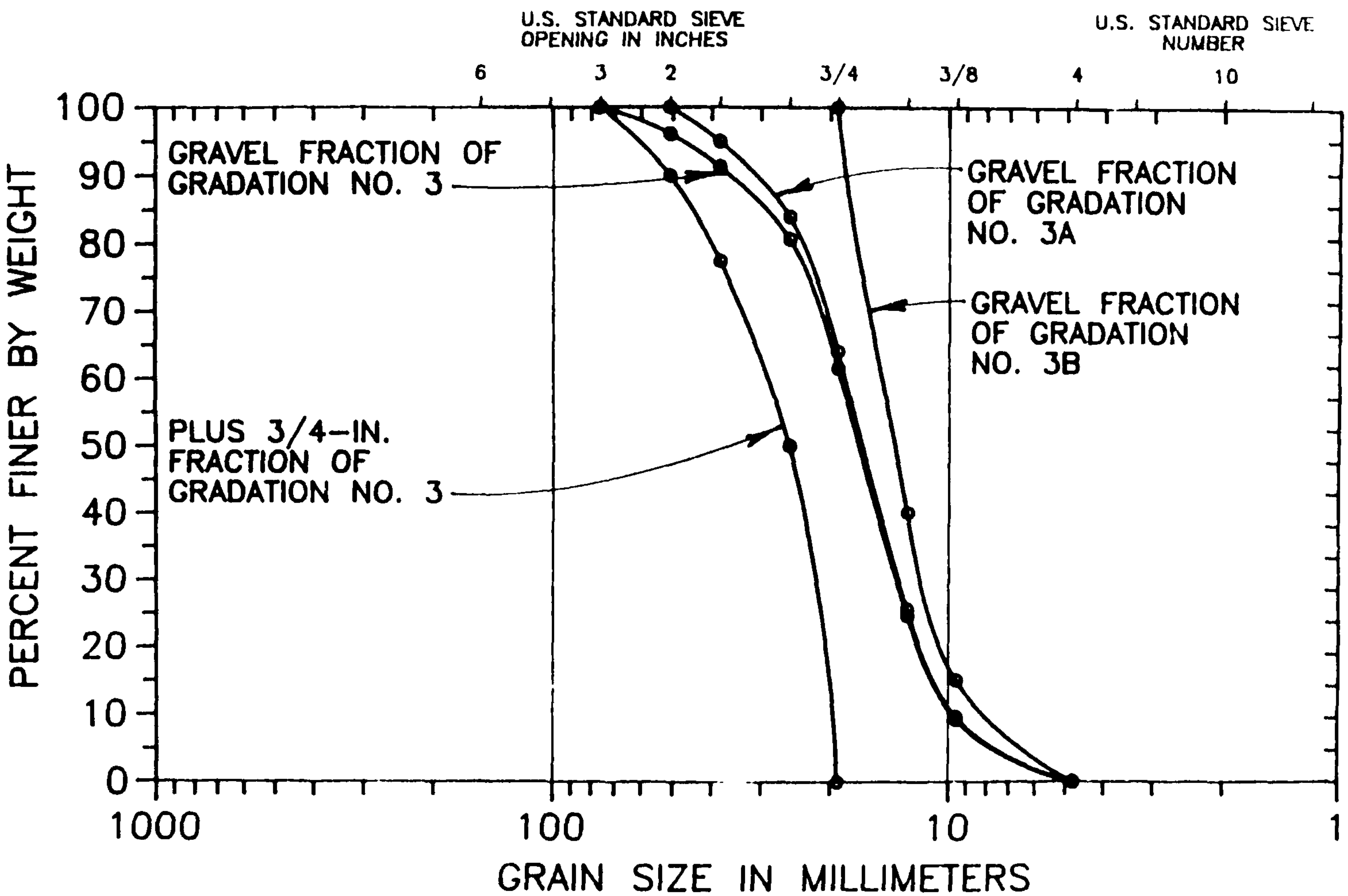


Figure 71. Grain-size distribution curves for gravel fraction of test gradation No.3, its associated fractions and its plus 3/4-in. fraction

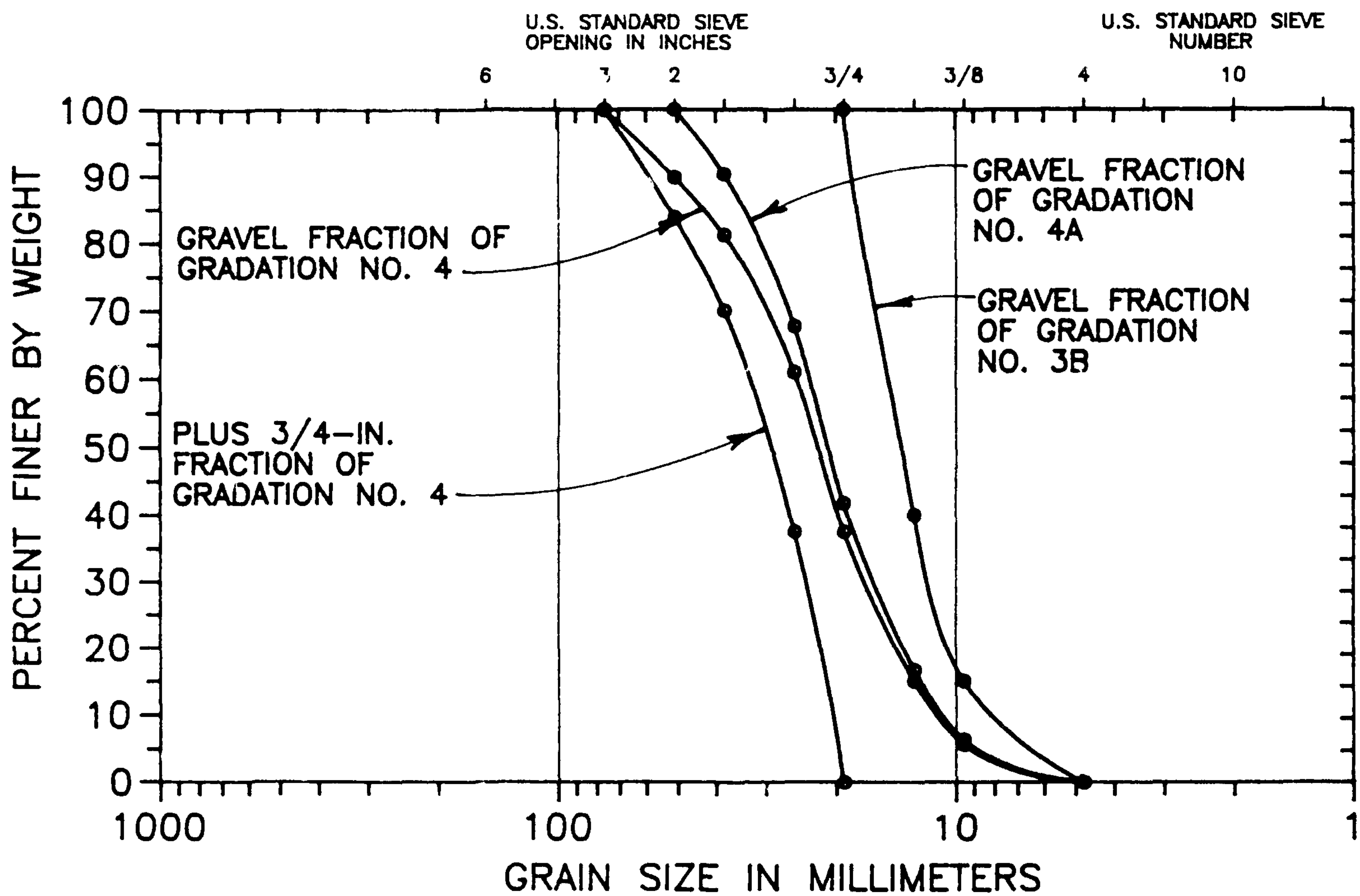


Figure 72. Grain-size distribution curves for gravel fraction of test gradation No.4, its associated fractions and its plus 3/4-in. fraction

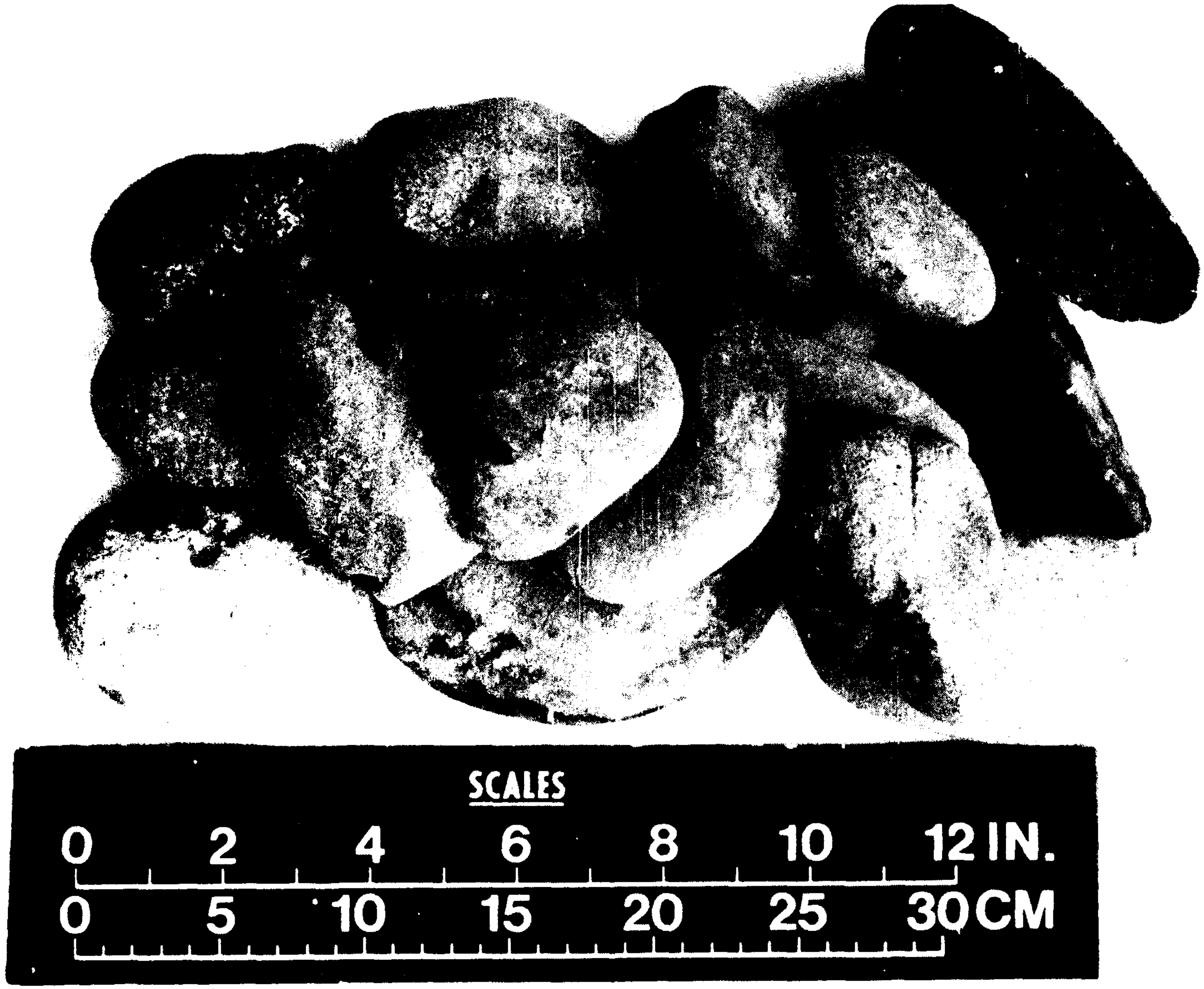


Figure 73. Washed gravel used in the test gradations, 3- to 2-in. sizes

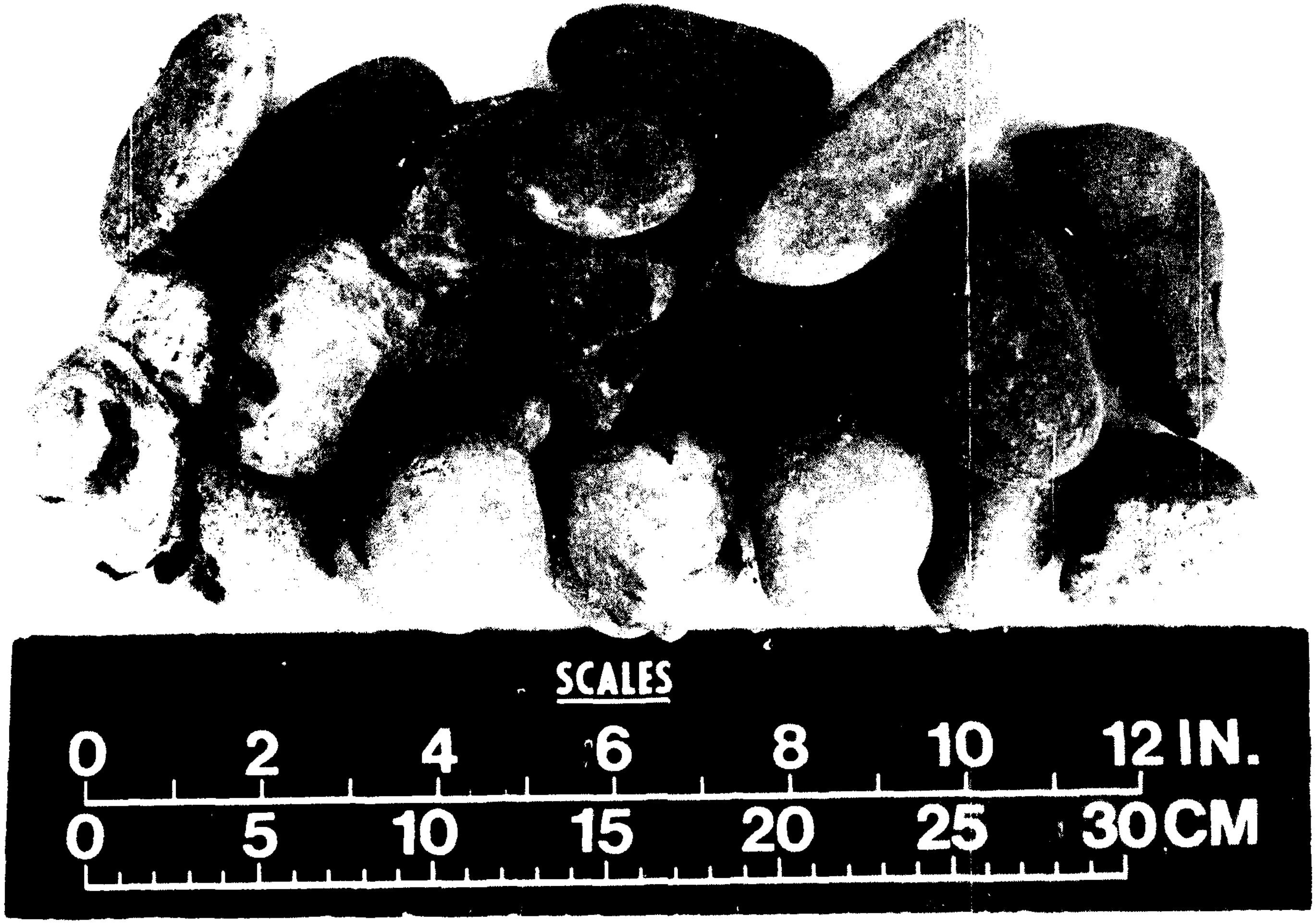


Figure 74. Washed gravel used in the test gradations, 2- to 1-1/2-in. sizes

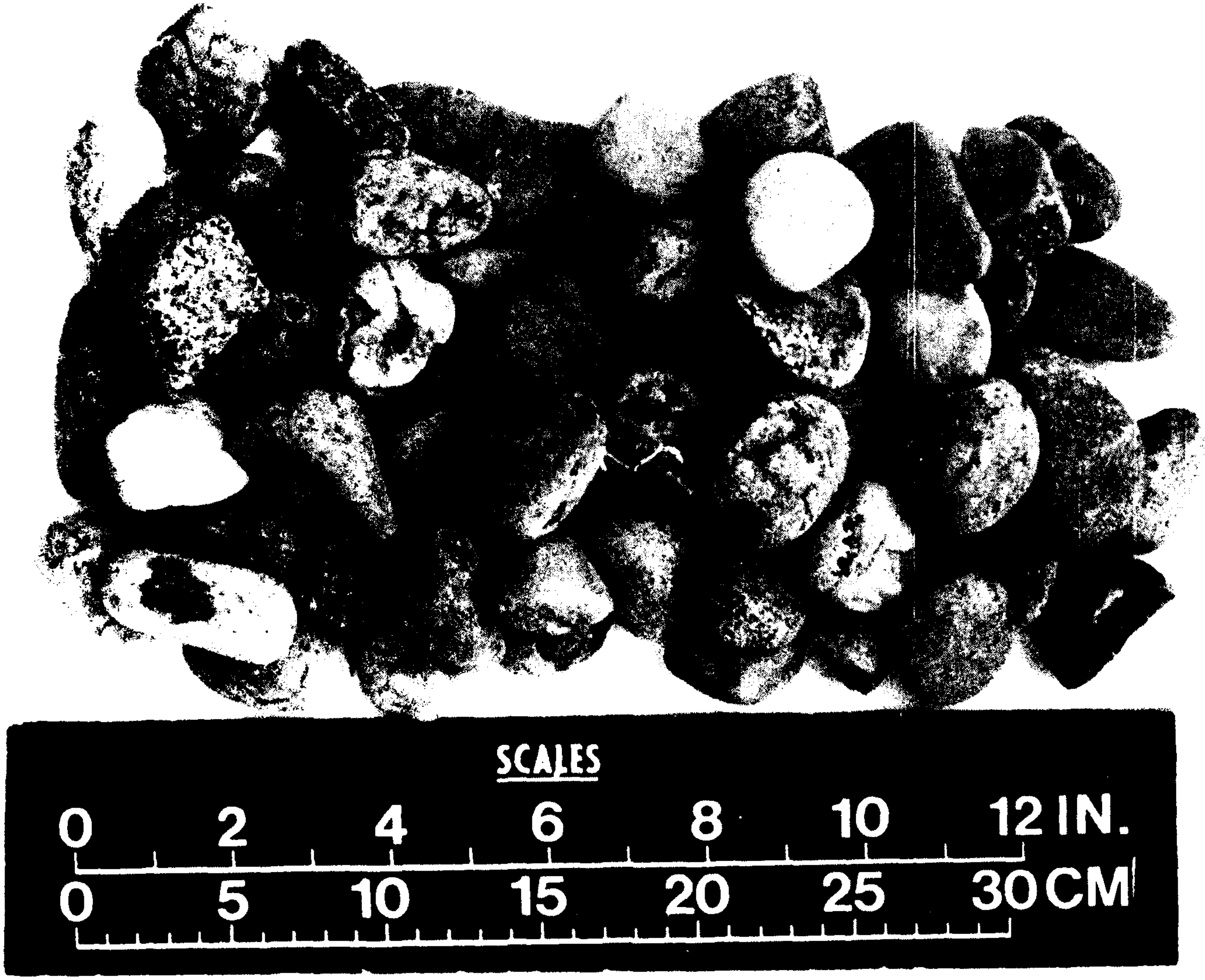


Figure 75. Washed gravel used in the test gradations, 1-1/2- to 1-in. sizes

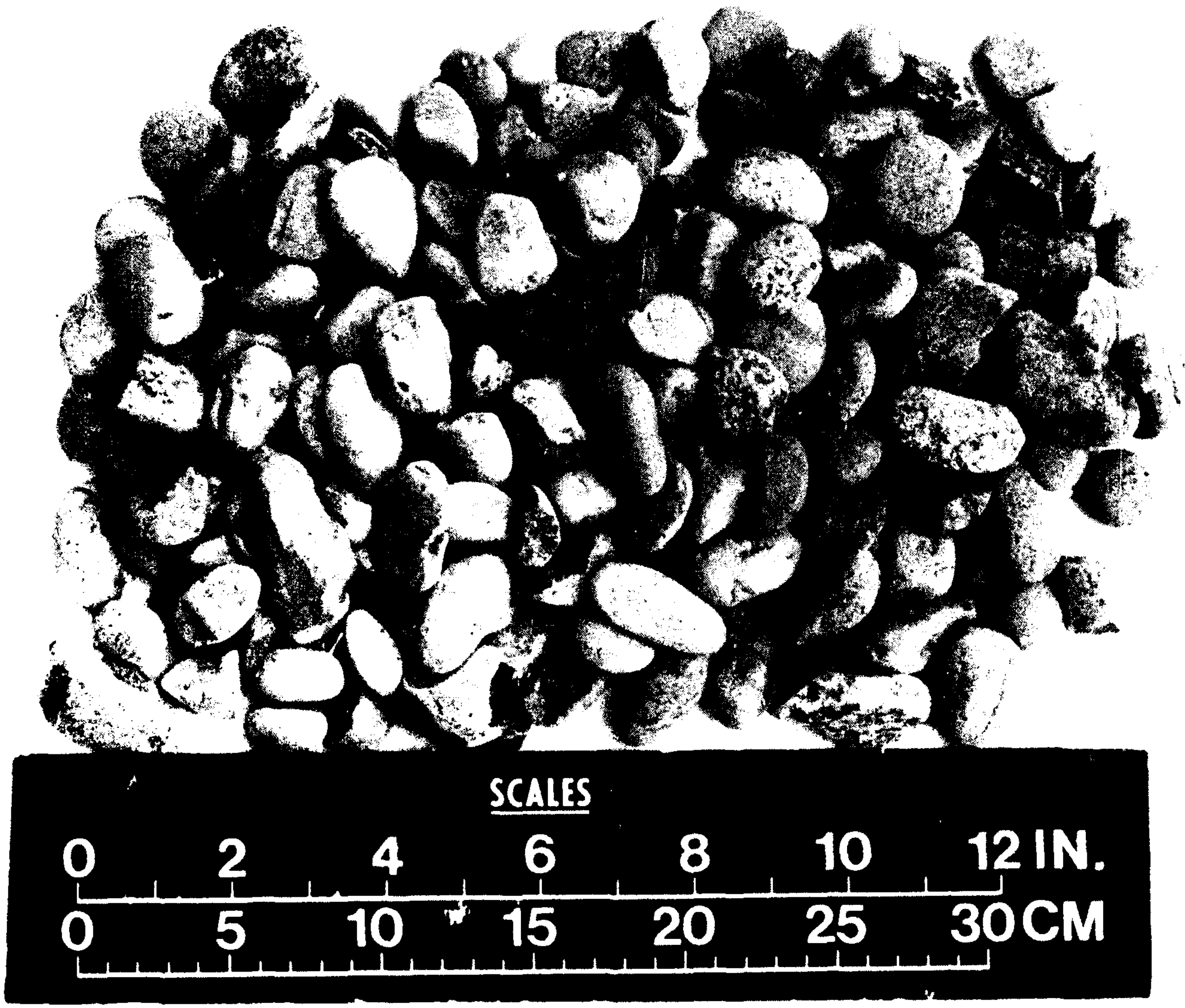


Figure 76. Washed gravel used in the test gradations, 1- to 3/4-in. sizes

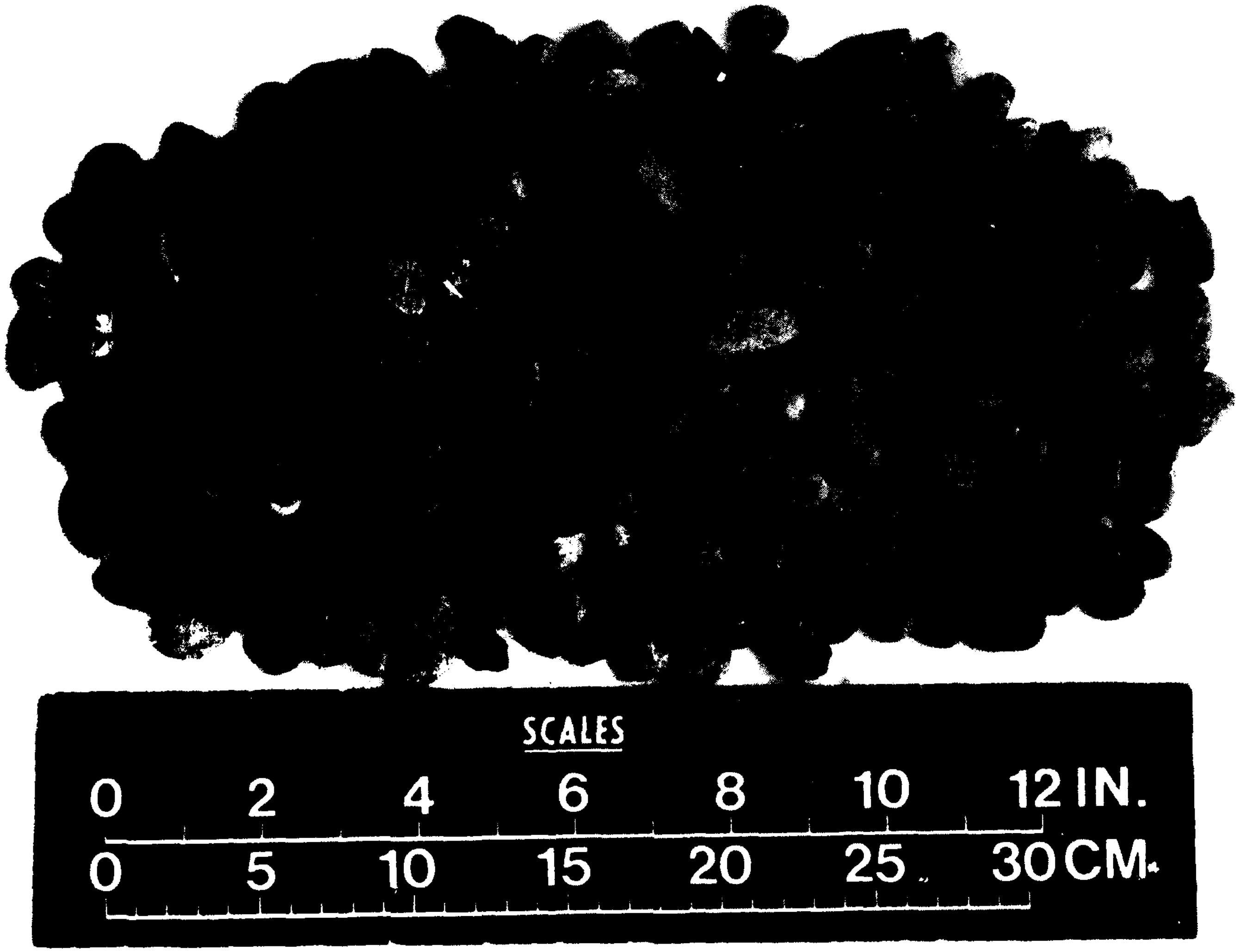


Figure 77. Washed gravel used in the test gradations, 3/4- to 1/2-in. sizes

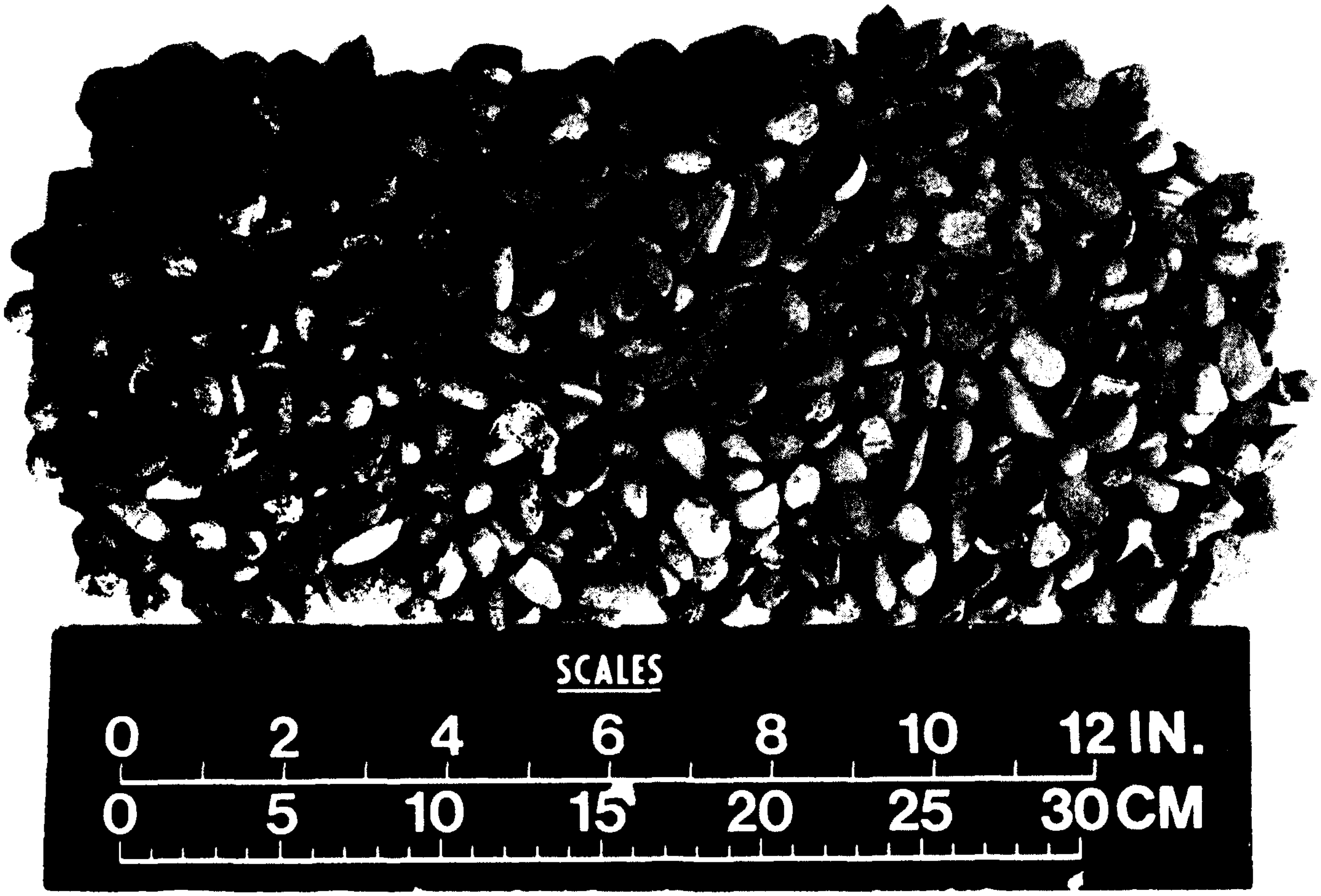


Figure 78. Washed gravel used in the test gradations, 1/2- to 3/8-in. sizes

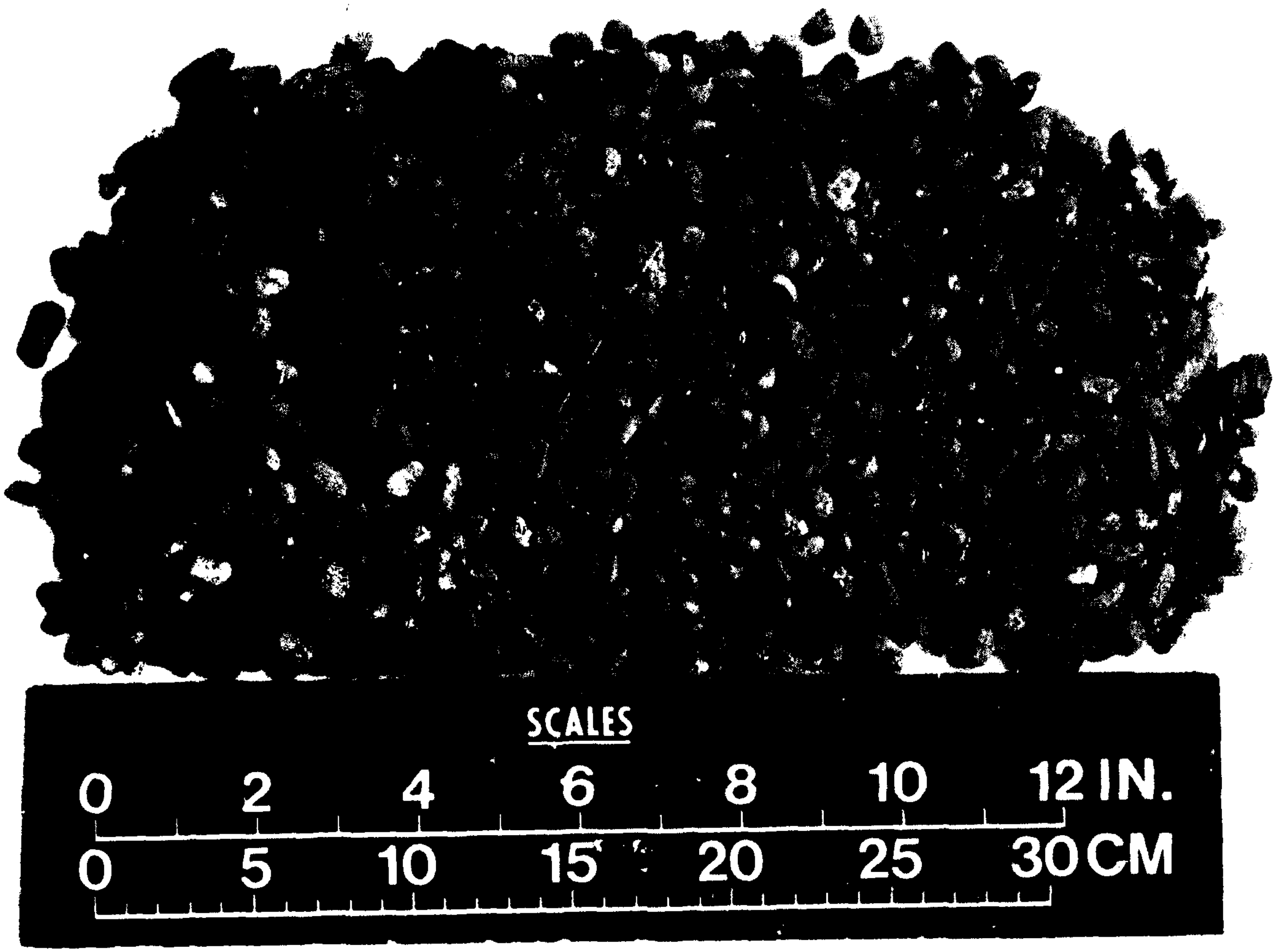


Figure 79. Washed gravel used in the test gradations, 3/8-in. to No.4 sizes

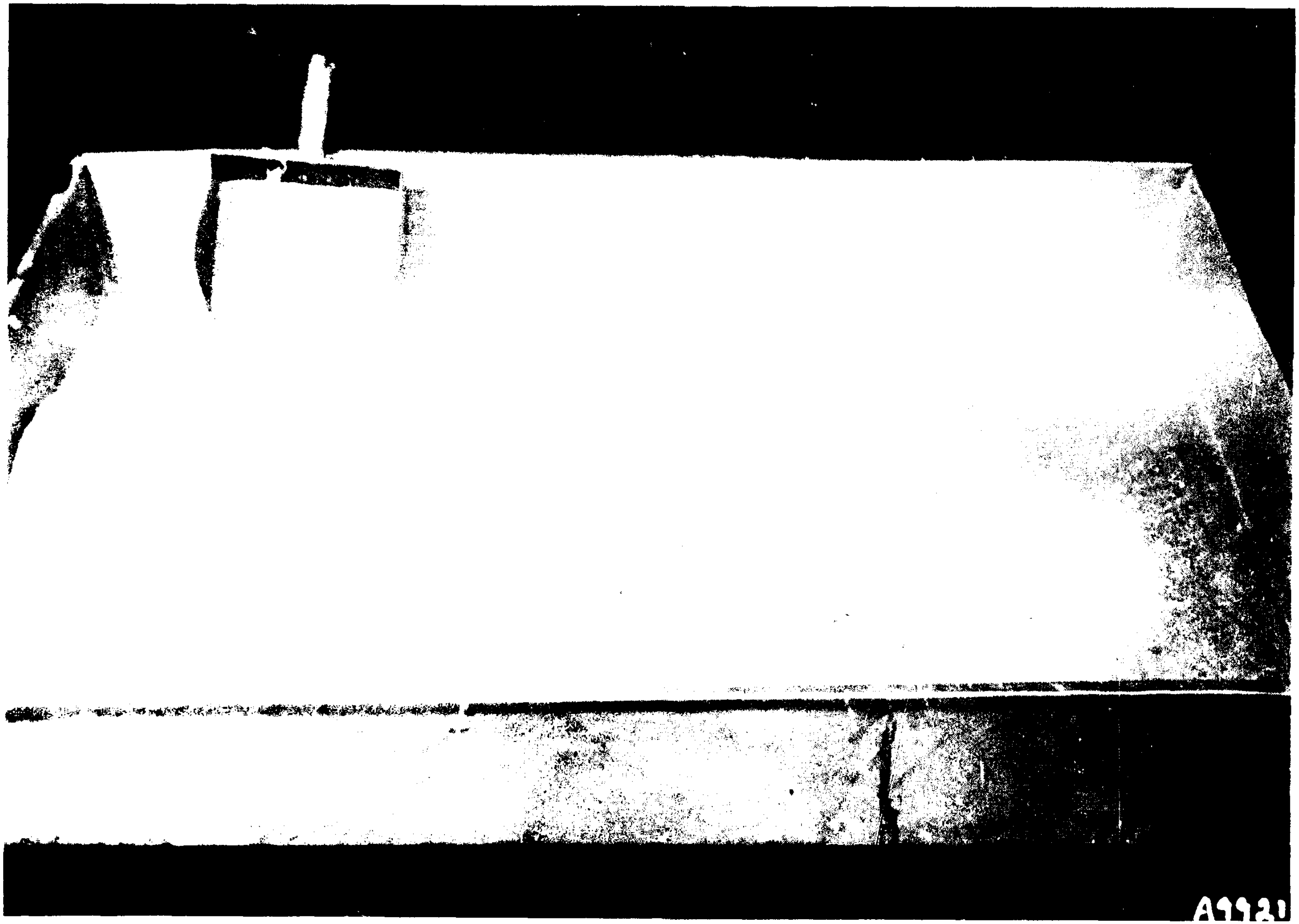


Figure 80. Predetermined amounts of sand (SP) and silt (ML) prior to mixing

Figure 81. Adding predetermined amount of water to sand and silt mixture

Figure 82. Mixing soil and water by hand prior to pushing through 1/4-in. hardware cloth

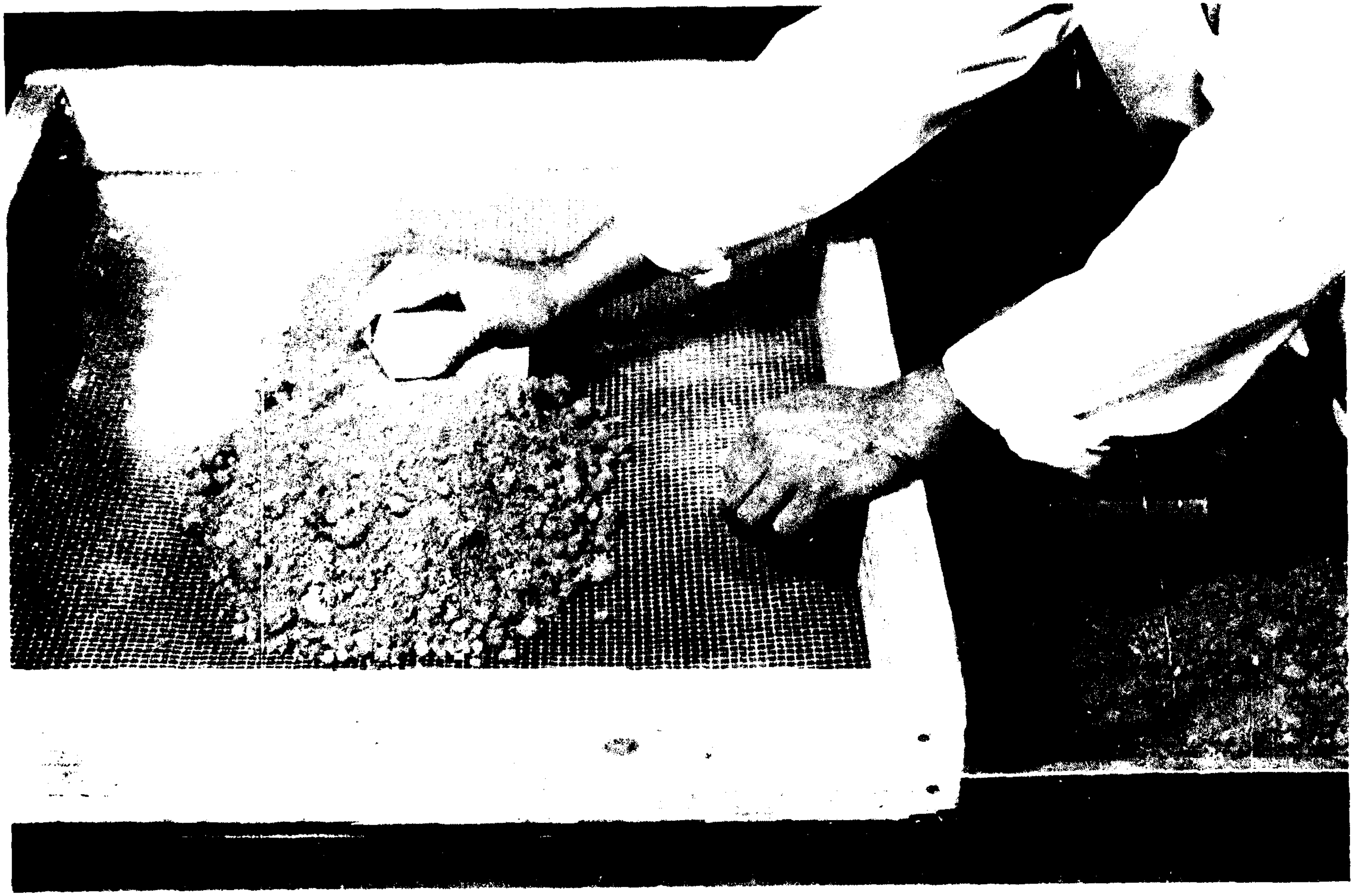


Figure 83. Pushing moistened soil through 1/4-in. hardware cloth to break down aggregations prior to curing in sealed containers

Figure 84. Gravel fraction for one layer of a full-scale specimen

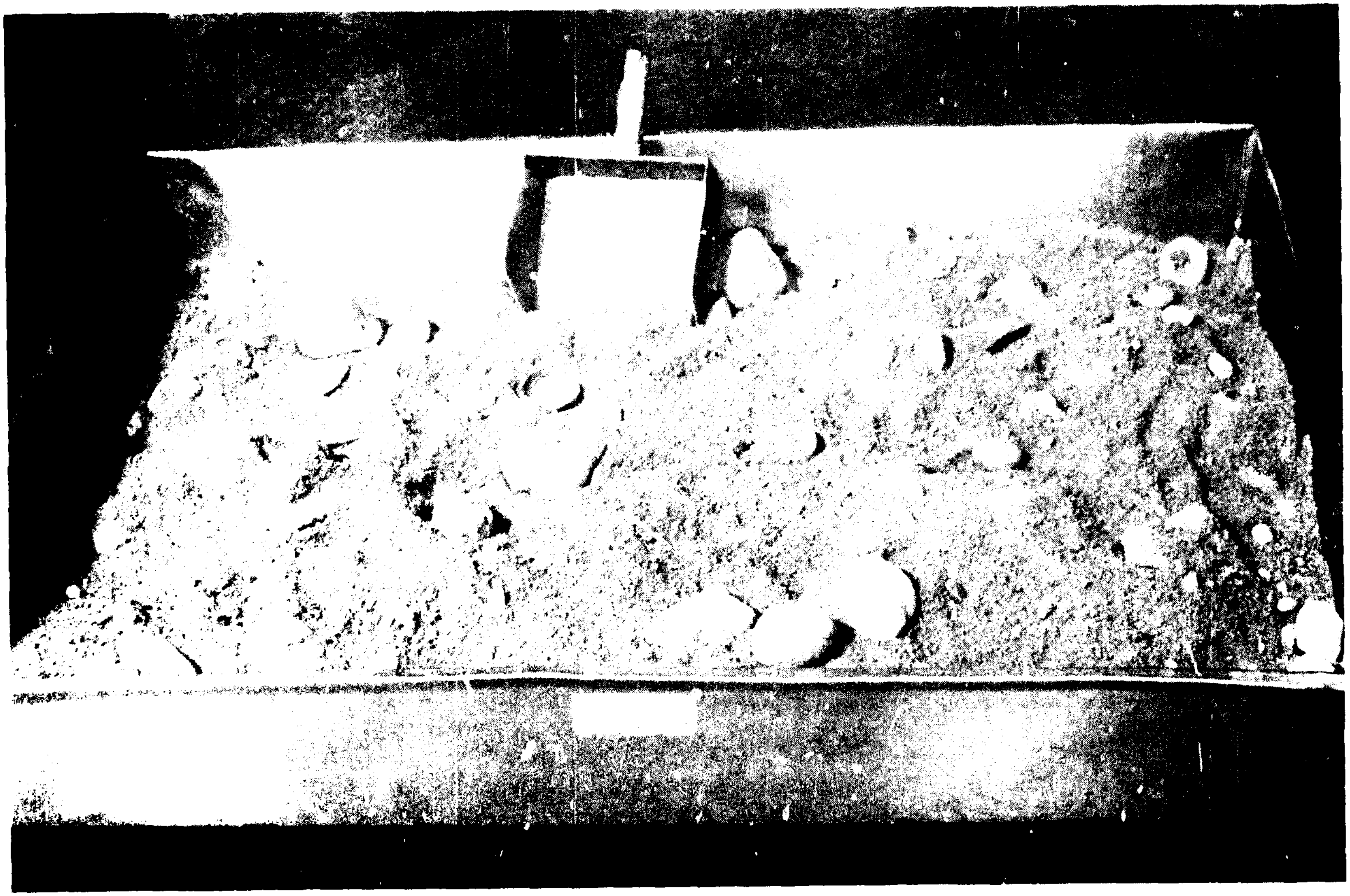


Figure 85. Combined batch for one layer of a full-scale specimen immediately prior to placement in the mold and compaction

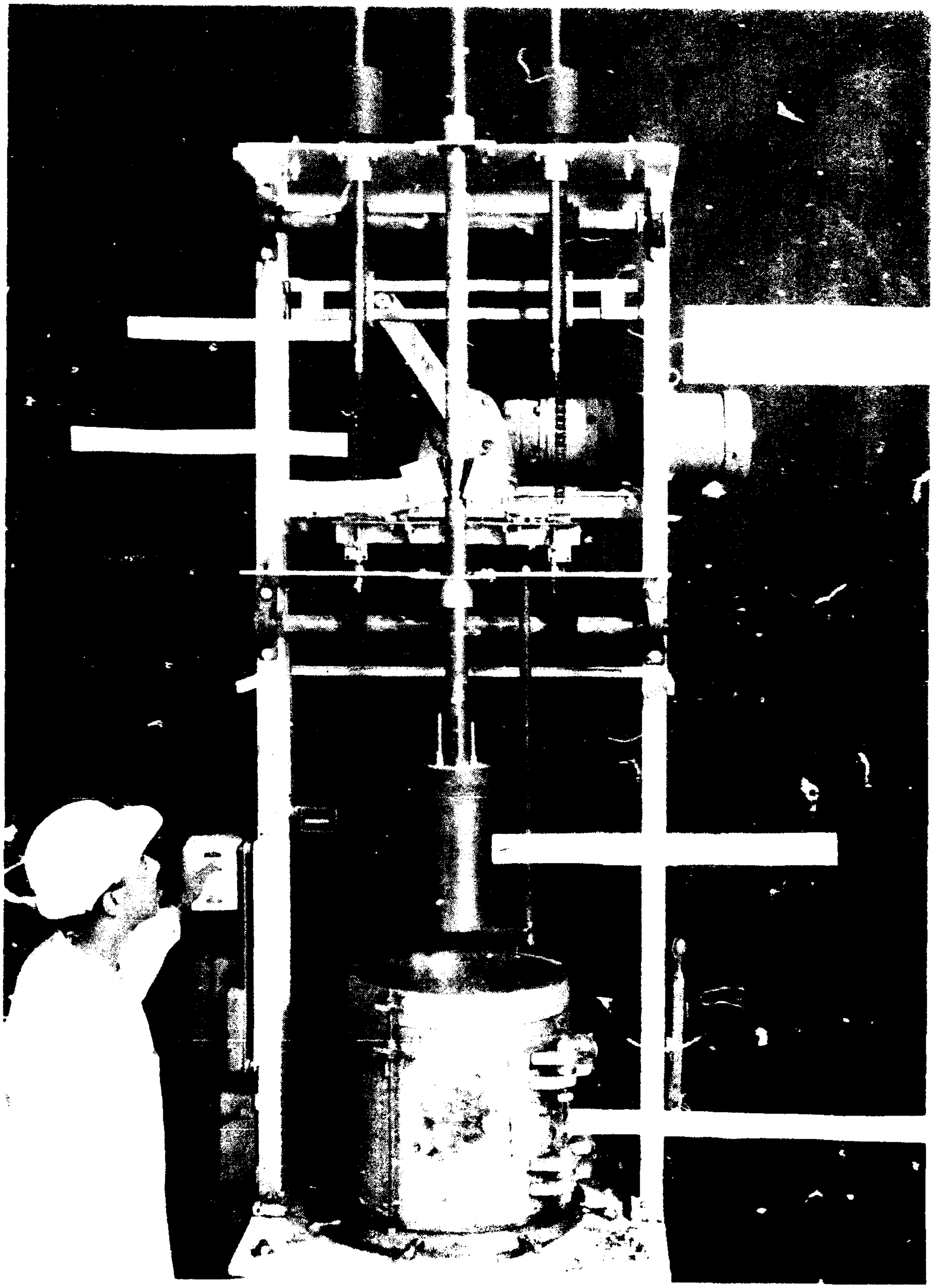


Figure 86. Howard Model H mechanical soil compactor

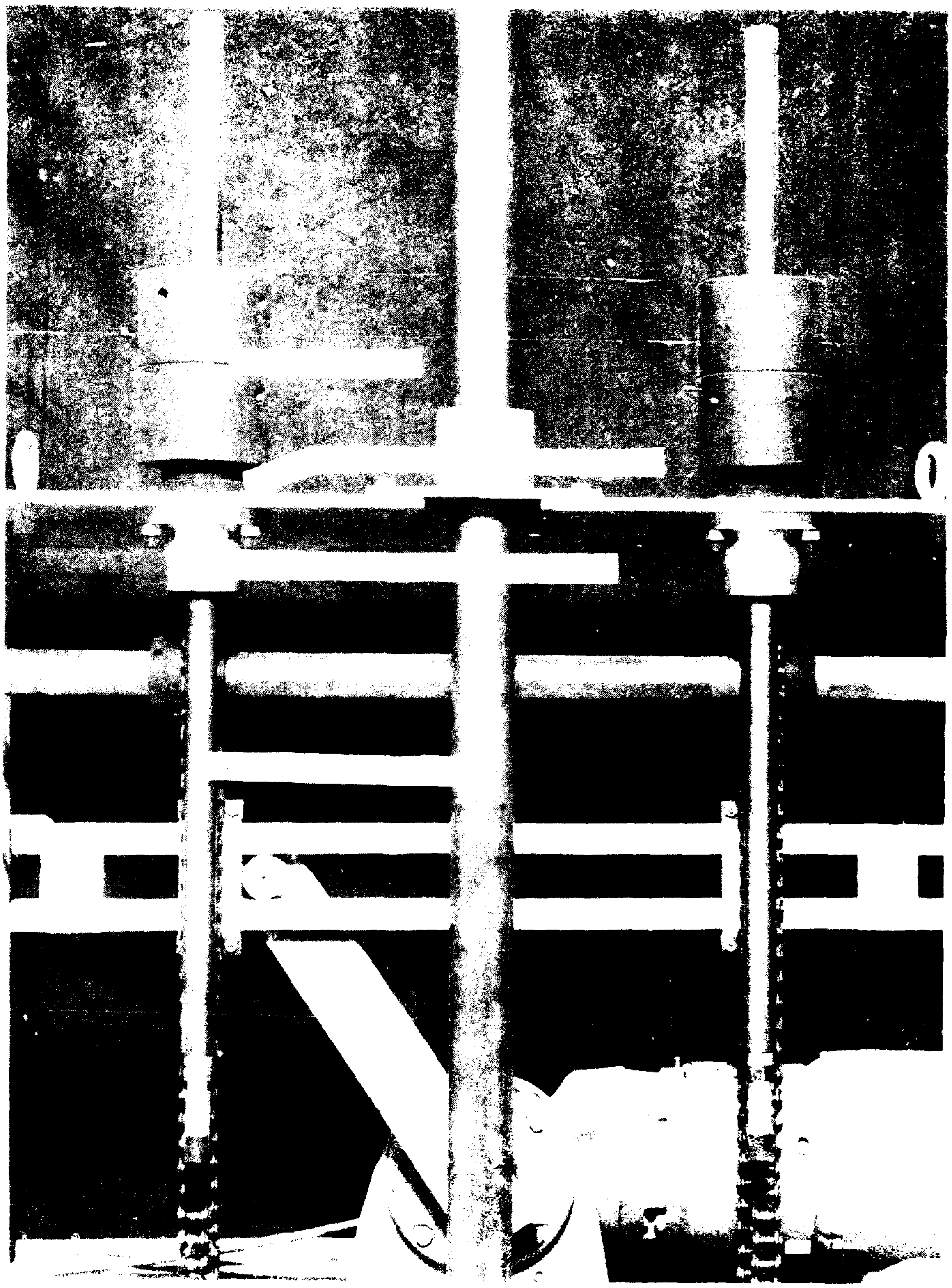


Figure 87. 1-in. diameter breaker rod assembly

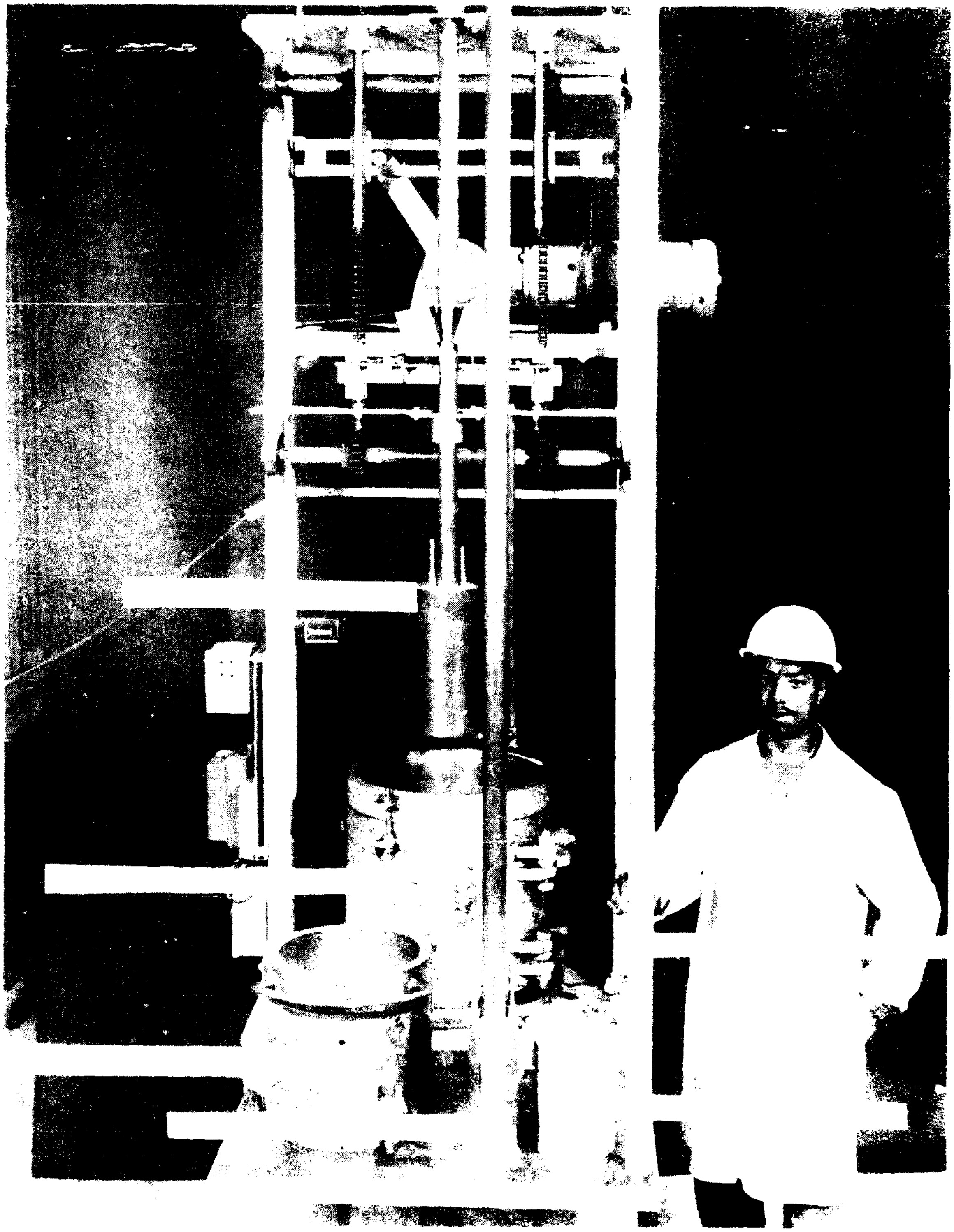


Figure 88. Molds and hammers

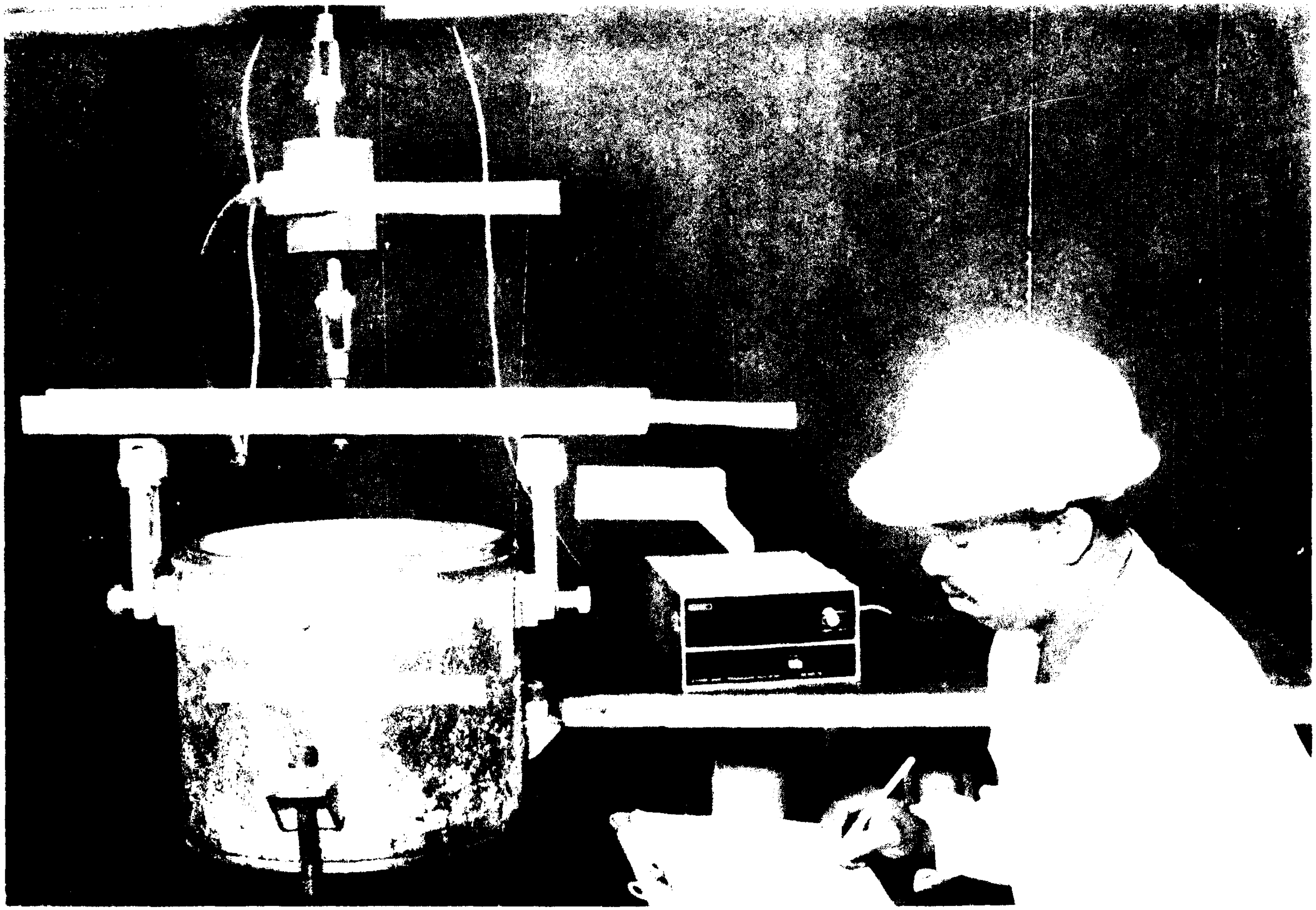


Figure 89. Load cell harness for obtaining specimen weights

Figure 90. Measuring distance from top of collar to compacted layer surface to determine specimen height

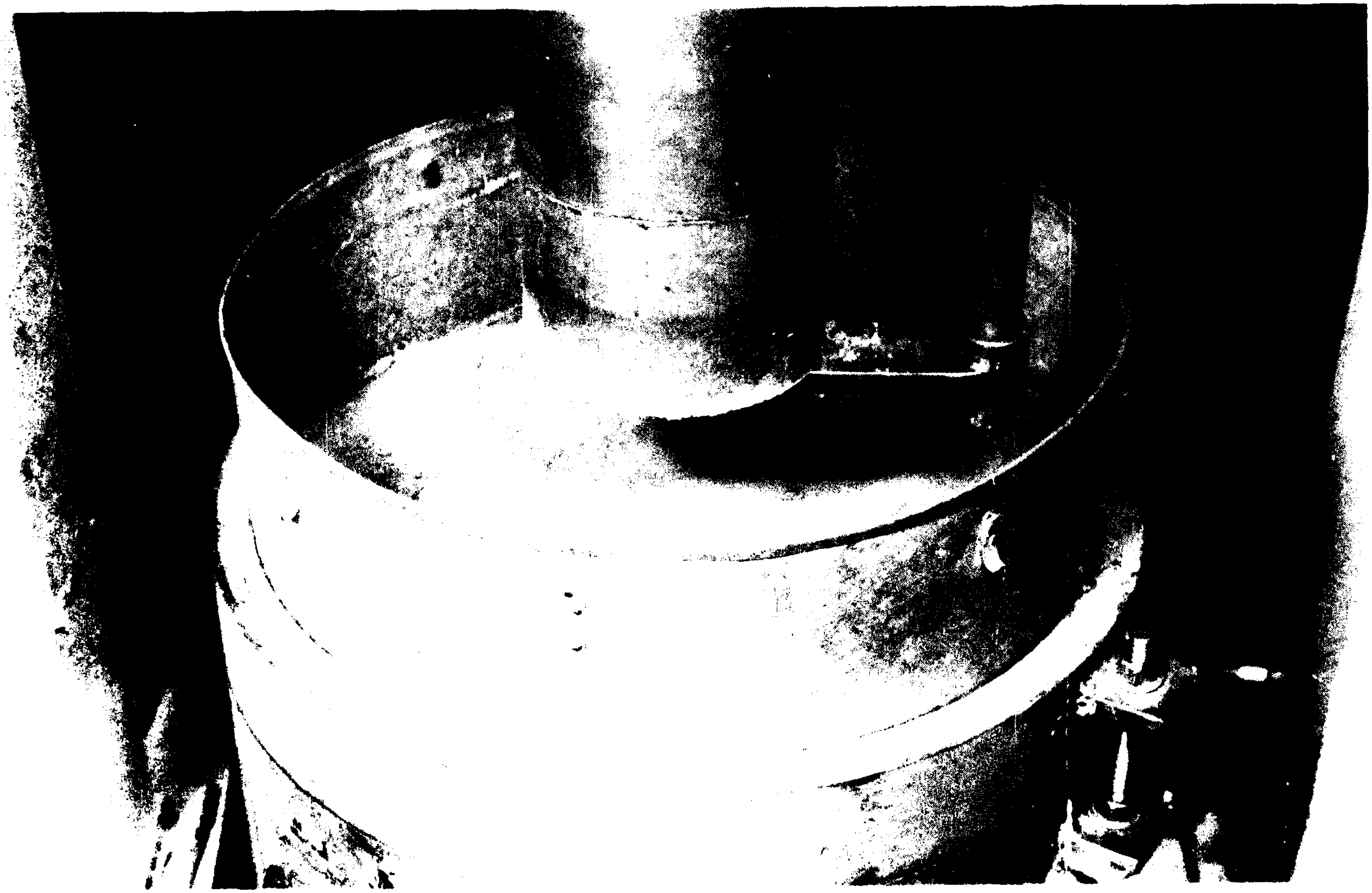
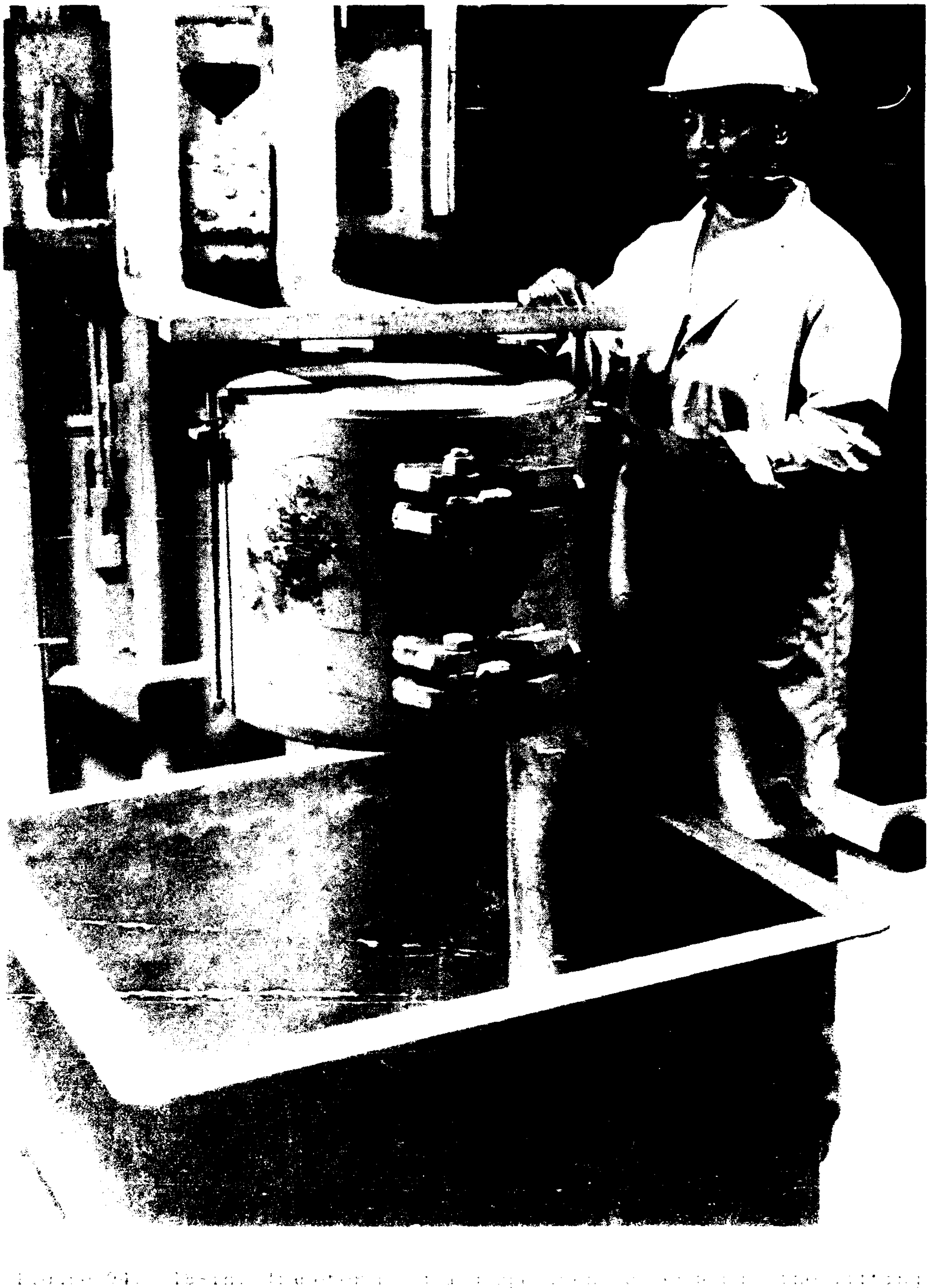


Figure 91. Final specimen layer in 18-in. diameter mold following light precompaction to level the surface

Figure 92. Final specimen layer in 18-in. diameter mold after compaction

Figure 93. Top of specimen in 18-in. diameter mold after trimming and patching



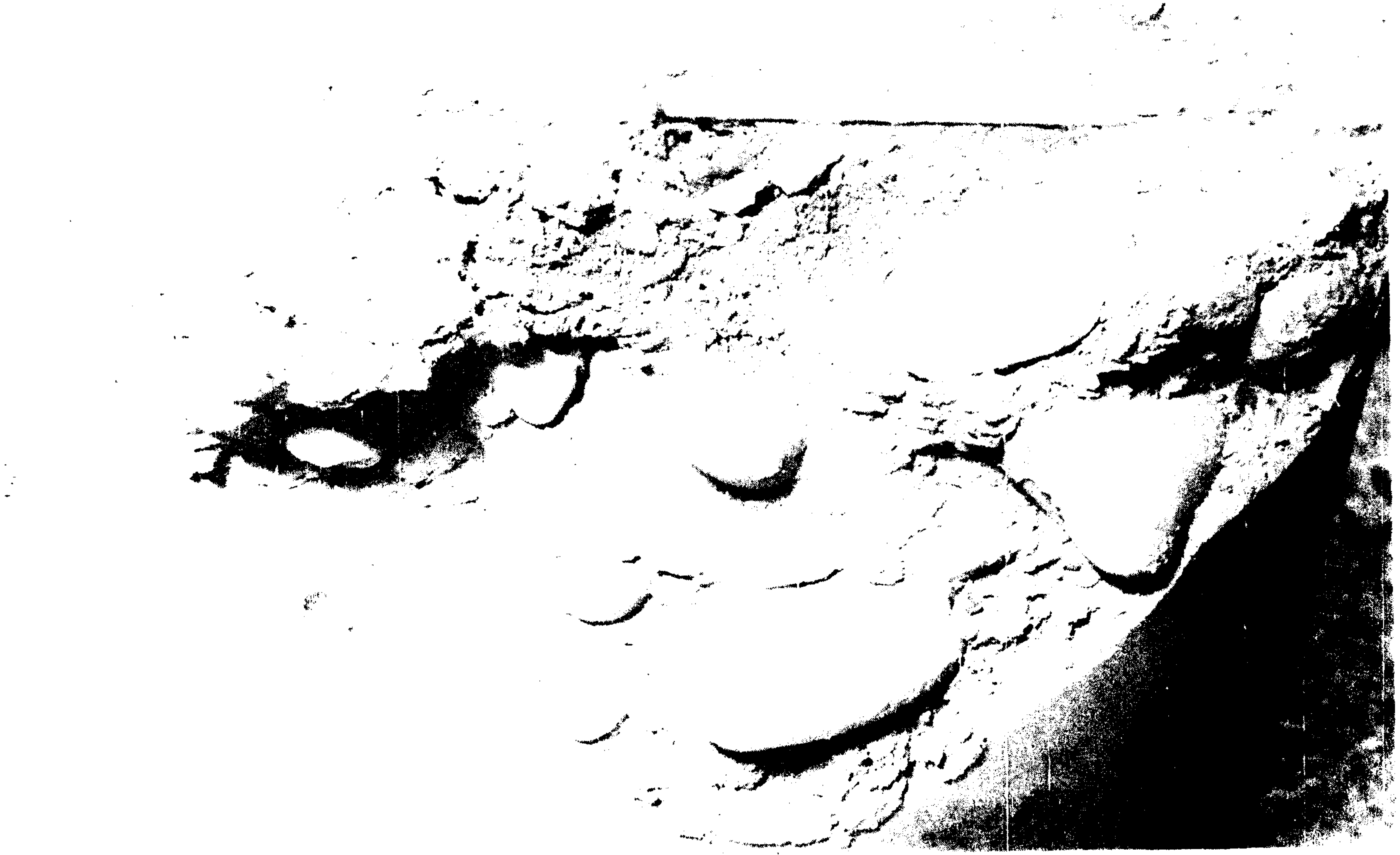


Figure 95. 18-in. diameter full-scale specimen (minus 3-in. gradation) after removal from the mold. Portion of specimen has been removed to show large particles

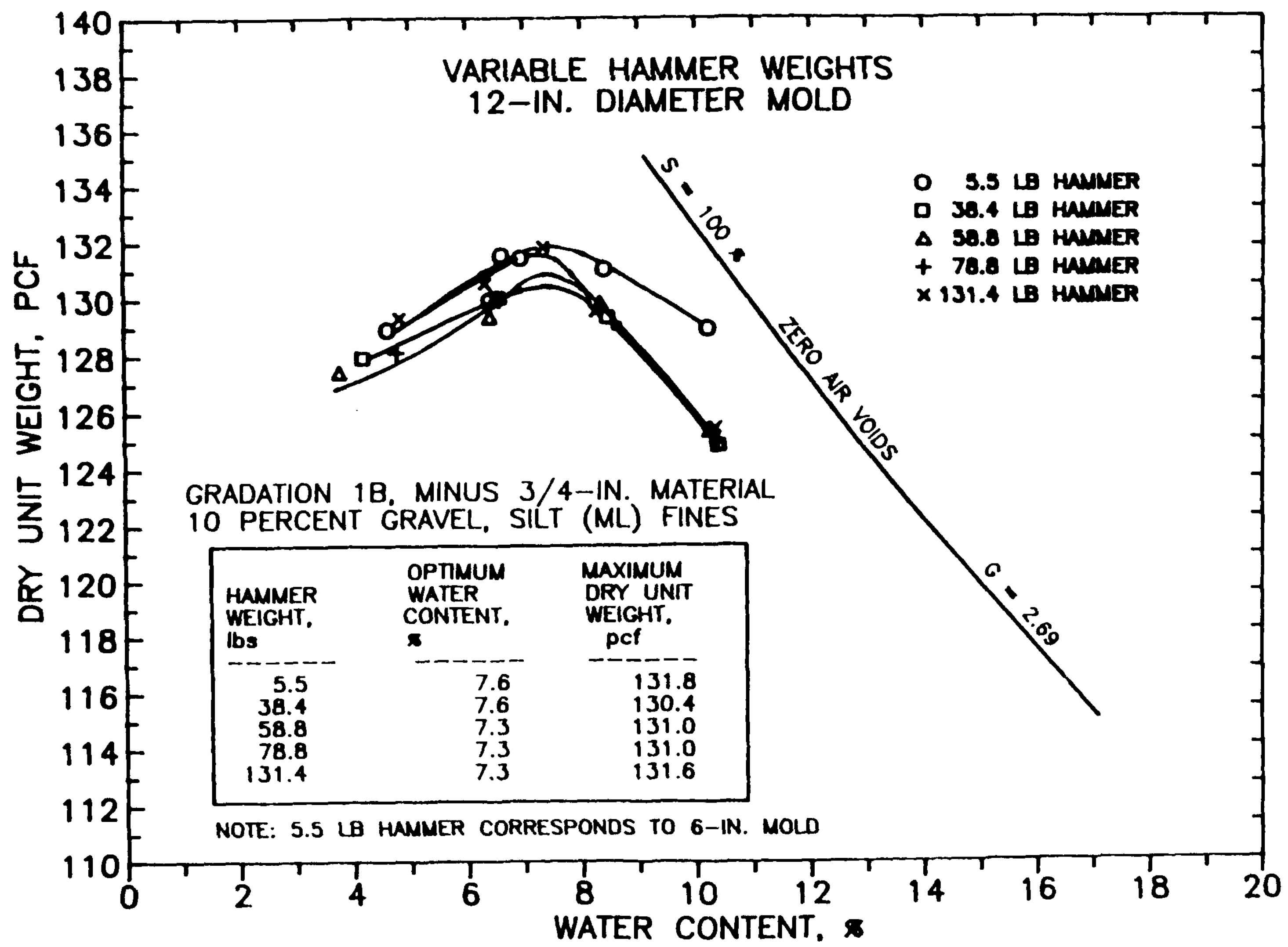


Figure 96. Compaction curves for tests performed on gradation No. 1B with silt (ML) fines in 12-in. diameter mold to determine effects of variable hammer weight

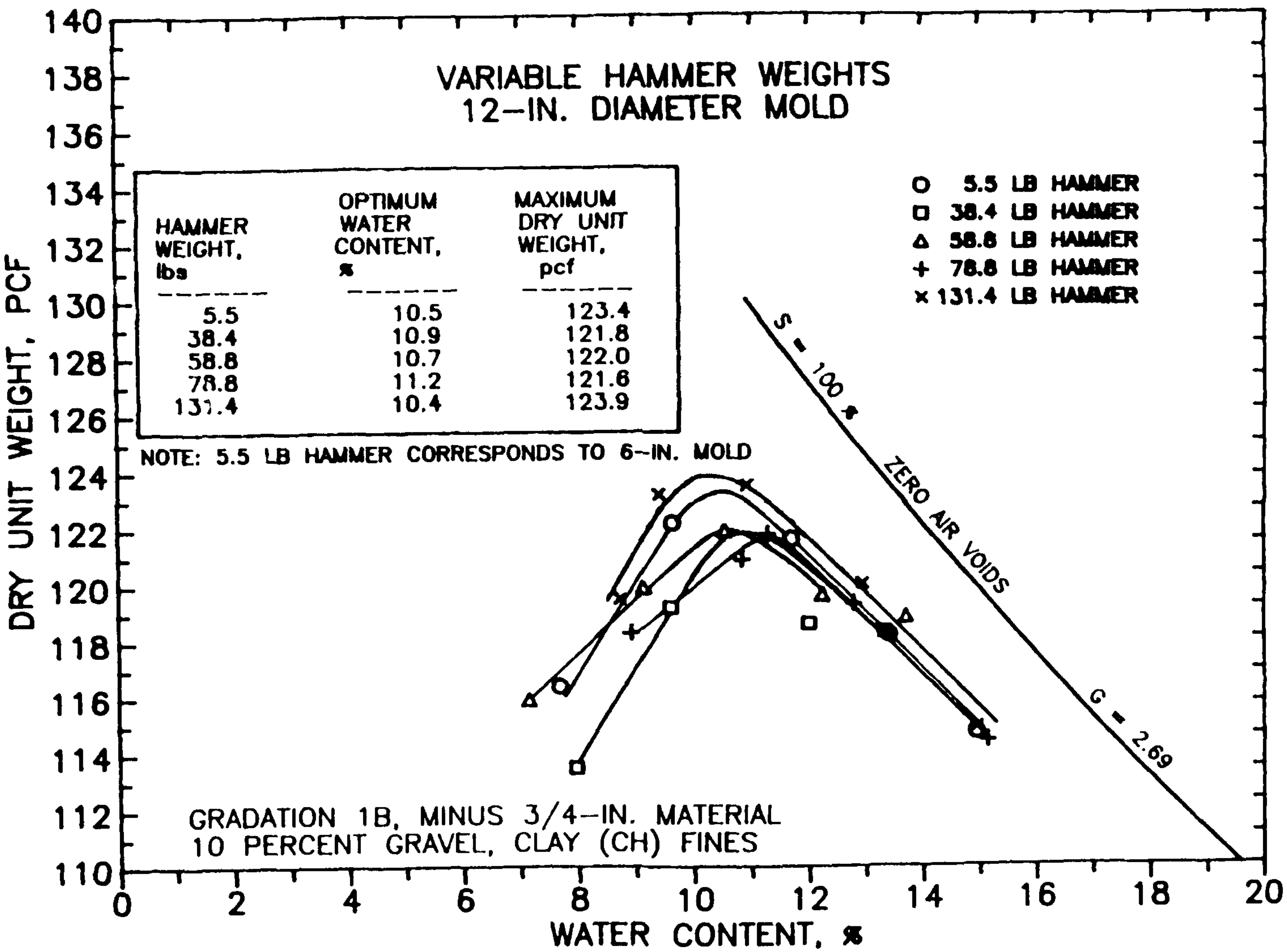


Figure 97. Compaction curves for tests performed on gradation No. 1B with clay (CH) fines in 12-in. diameter mold to determine effects of variable hammer weight

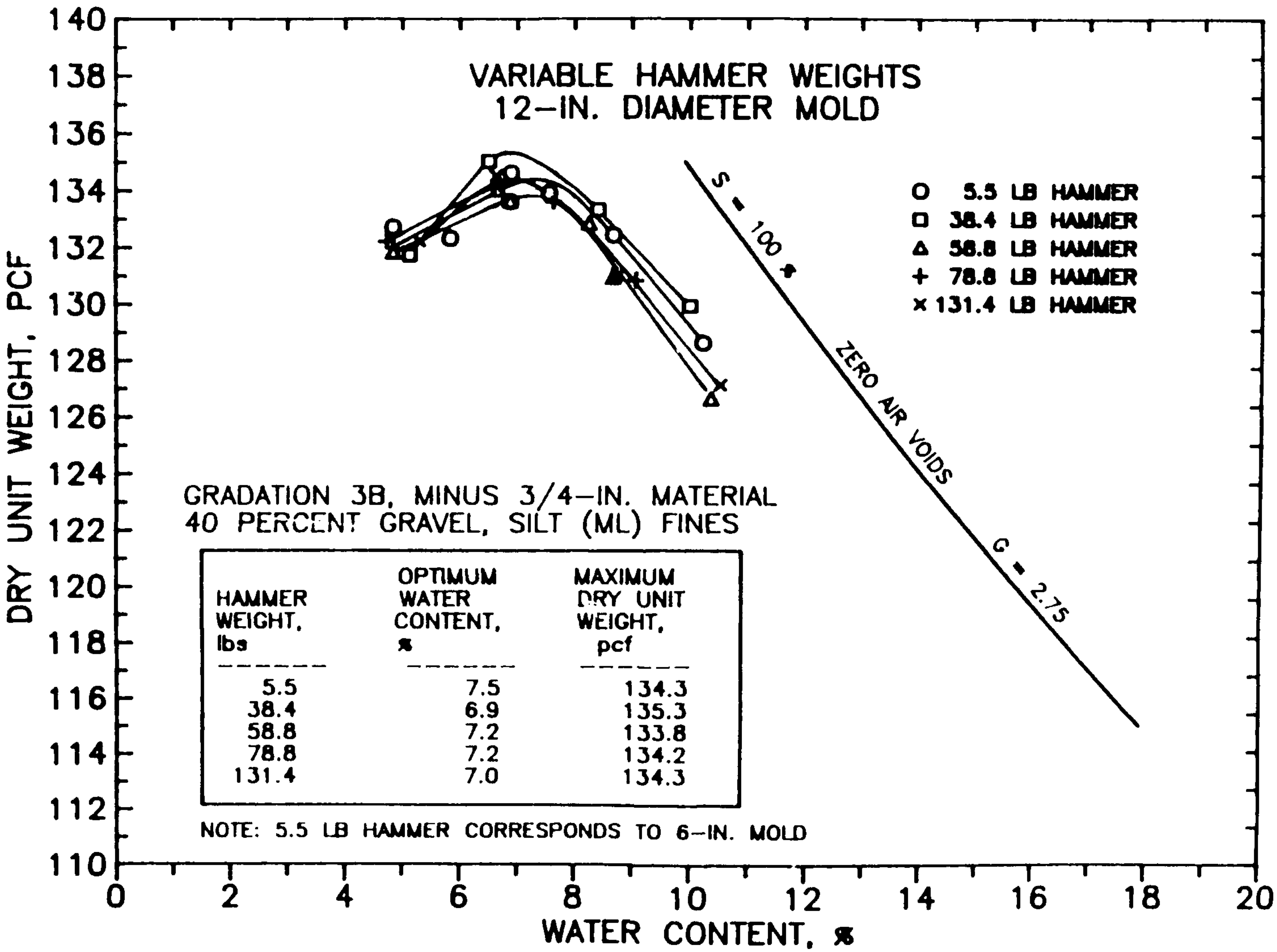


Figure 98. Compaction curves for tests performed on gradation No. 3B with silt (ML) fines in 12-in. diameter mold to determine effects of variable hammer weight

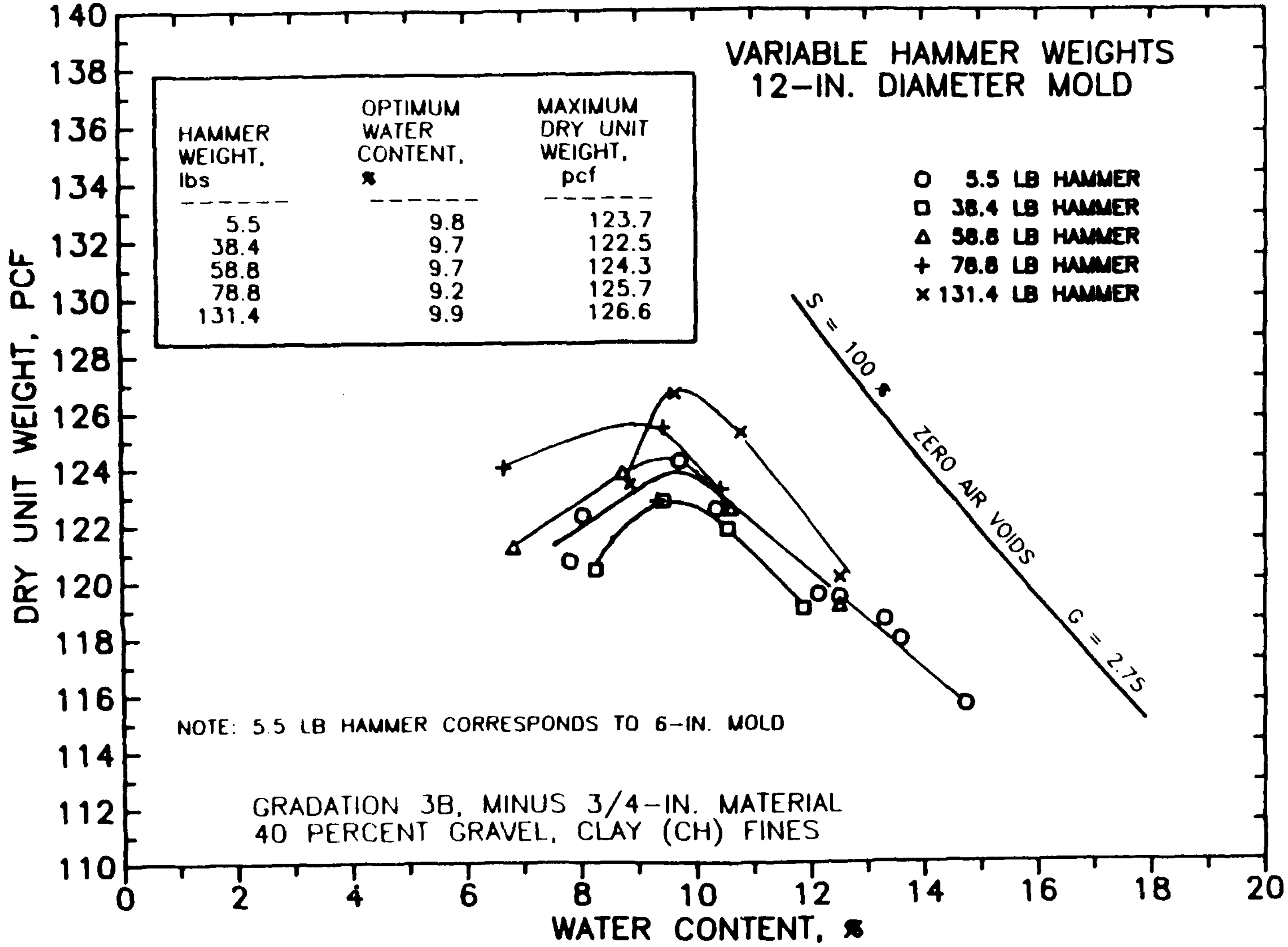


Figure 99. Compaction curves for tests performed on gradation No. 3B with clay (CH) fines in 12-in. diameter mold to determine effects of variable hammer weight

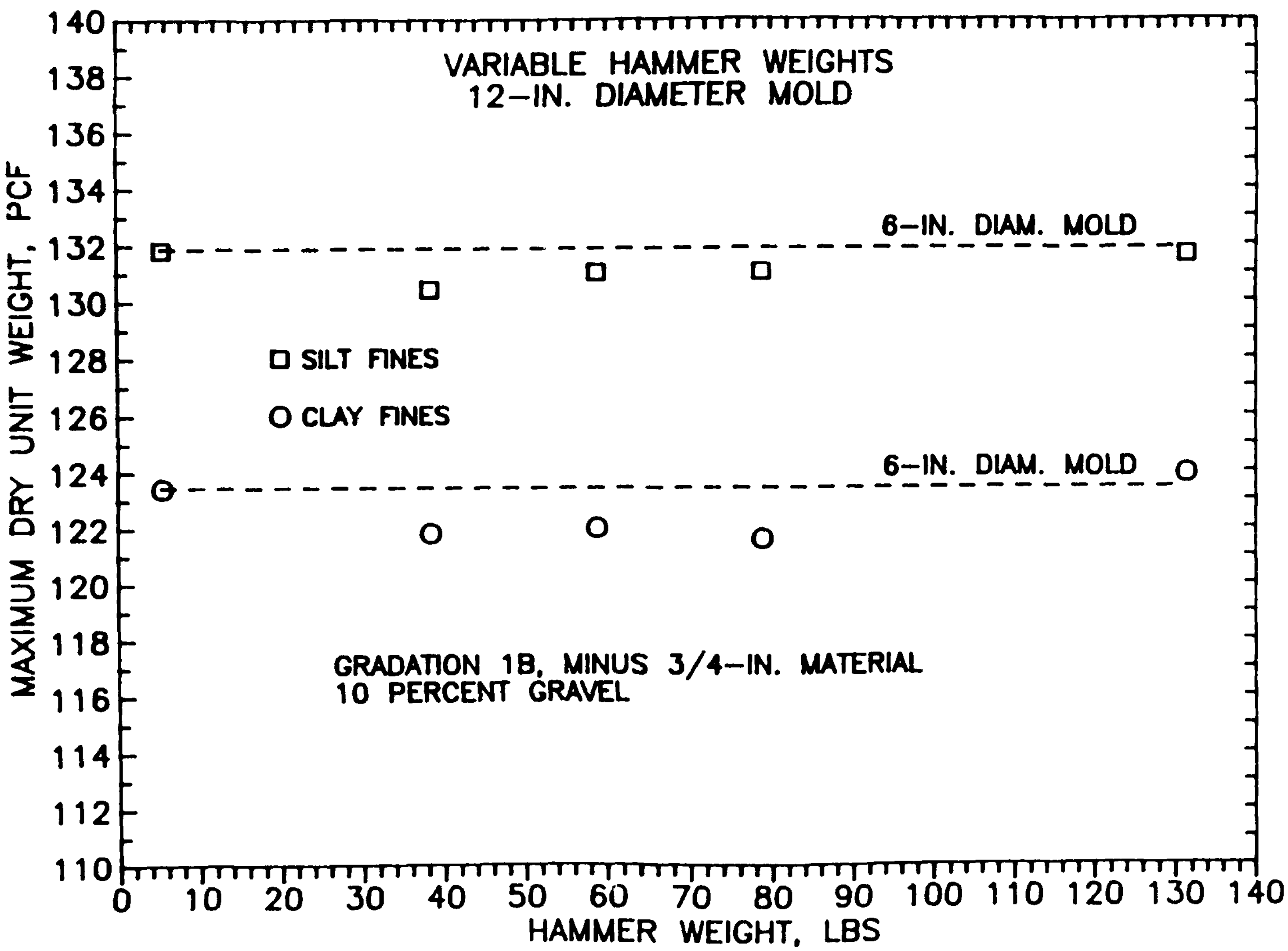


Figure 100. Maximum dry unit weight versus hammer weight for tests performed on gradation No. 1B in 12-in. diameter mold

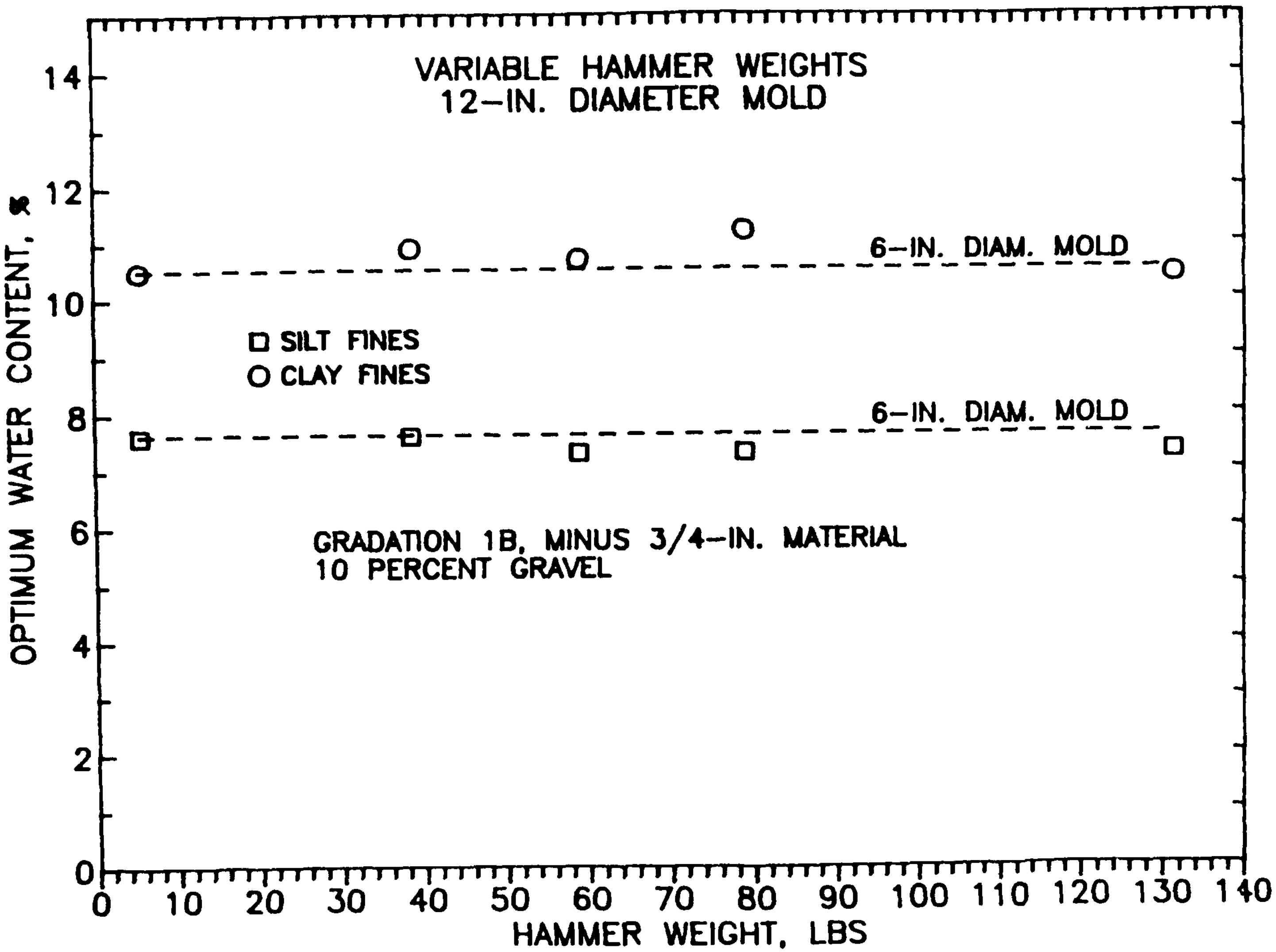


Figure 101. Optimum water content versus hammer weight for tests performed on gradation No. 1B in 12-in. diameter mold

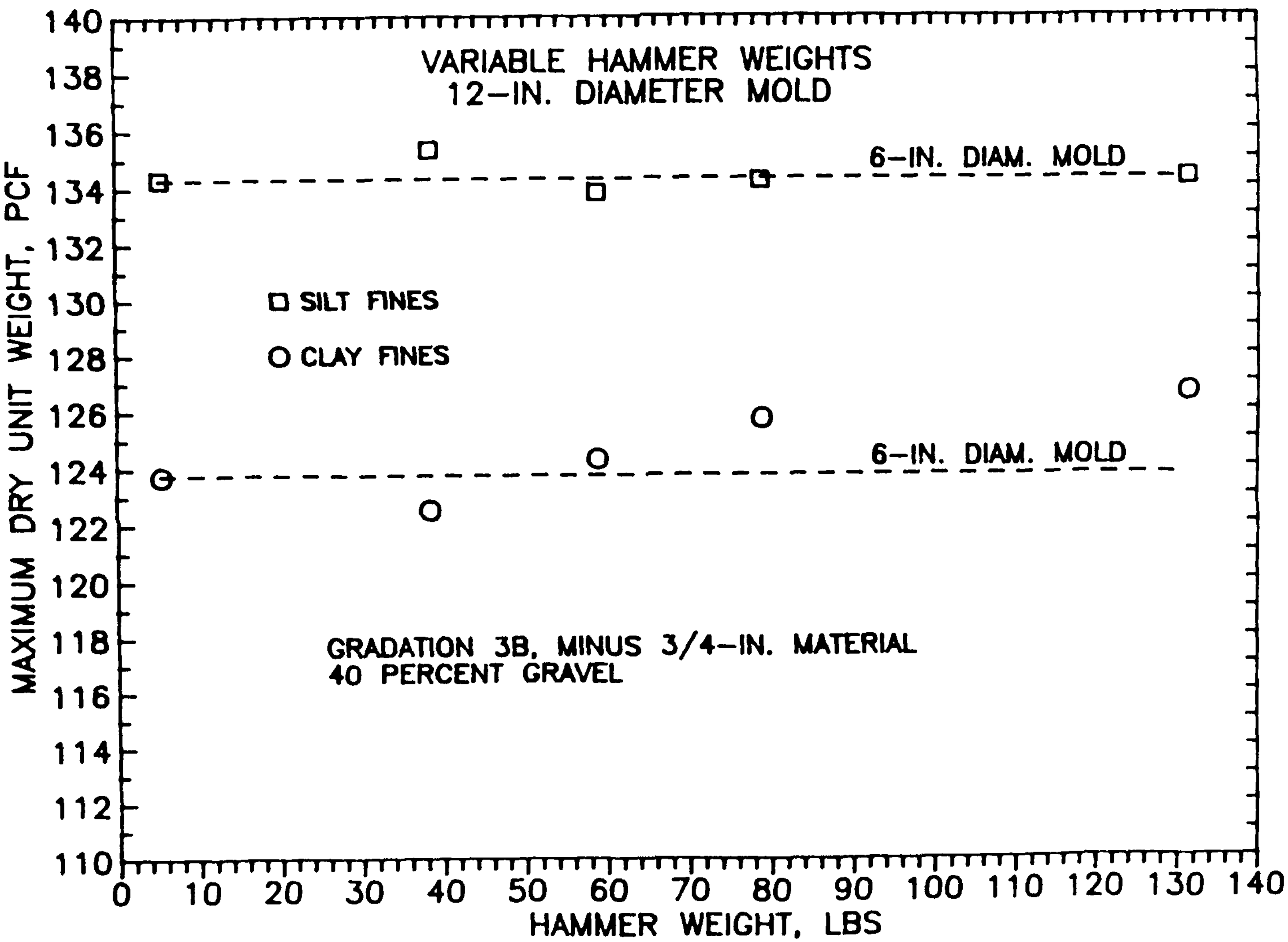


Figure 102. Maximum dry unit weight versus hammer weight for tests performed on gradation No. 3B in 12-in. diameter mold

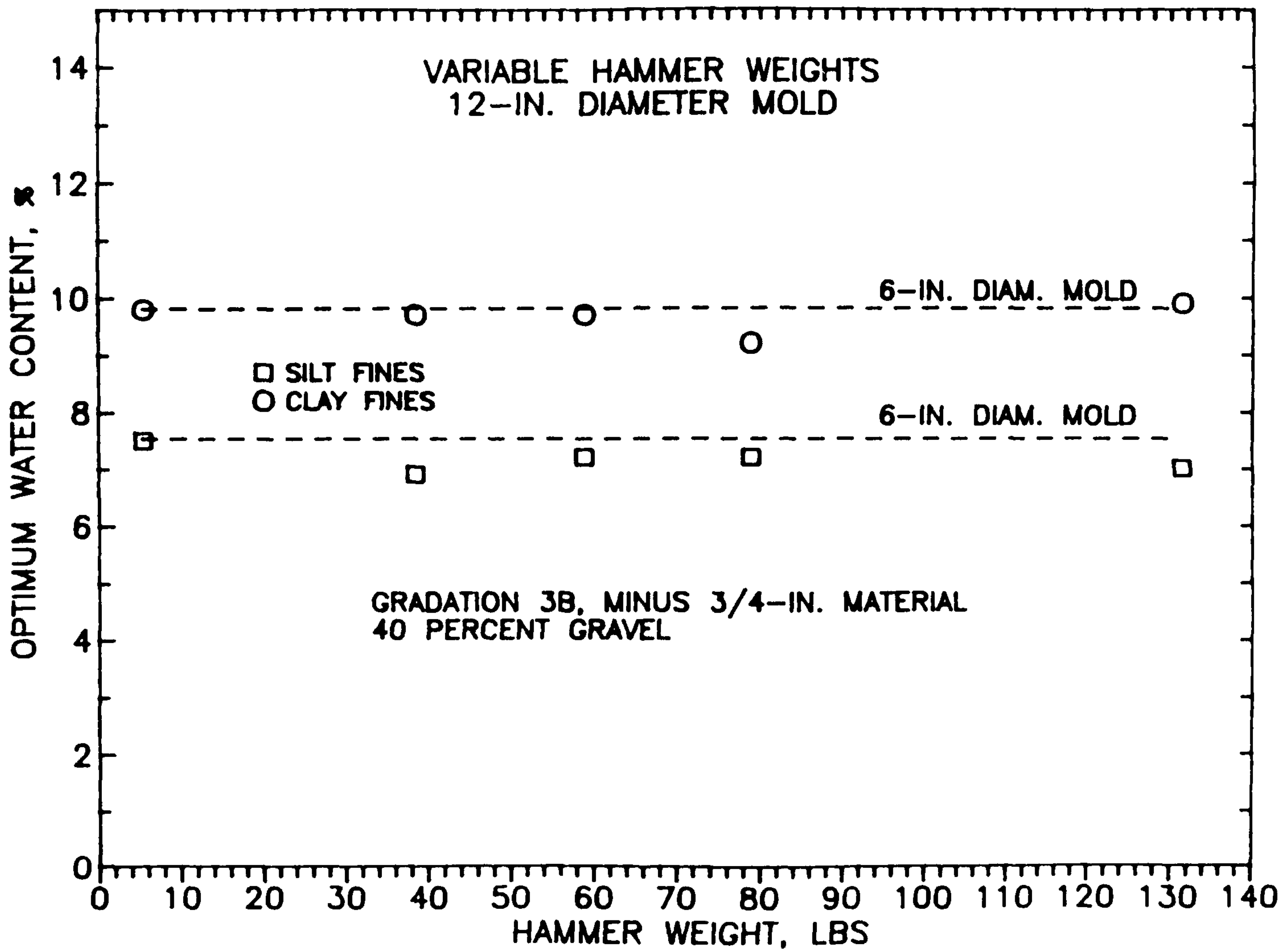


Figure 103. Optimum water content versus hammer weight for tests performed on gradation No. 3B in 12 in. diameter mold

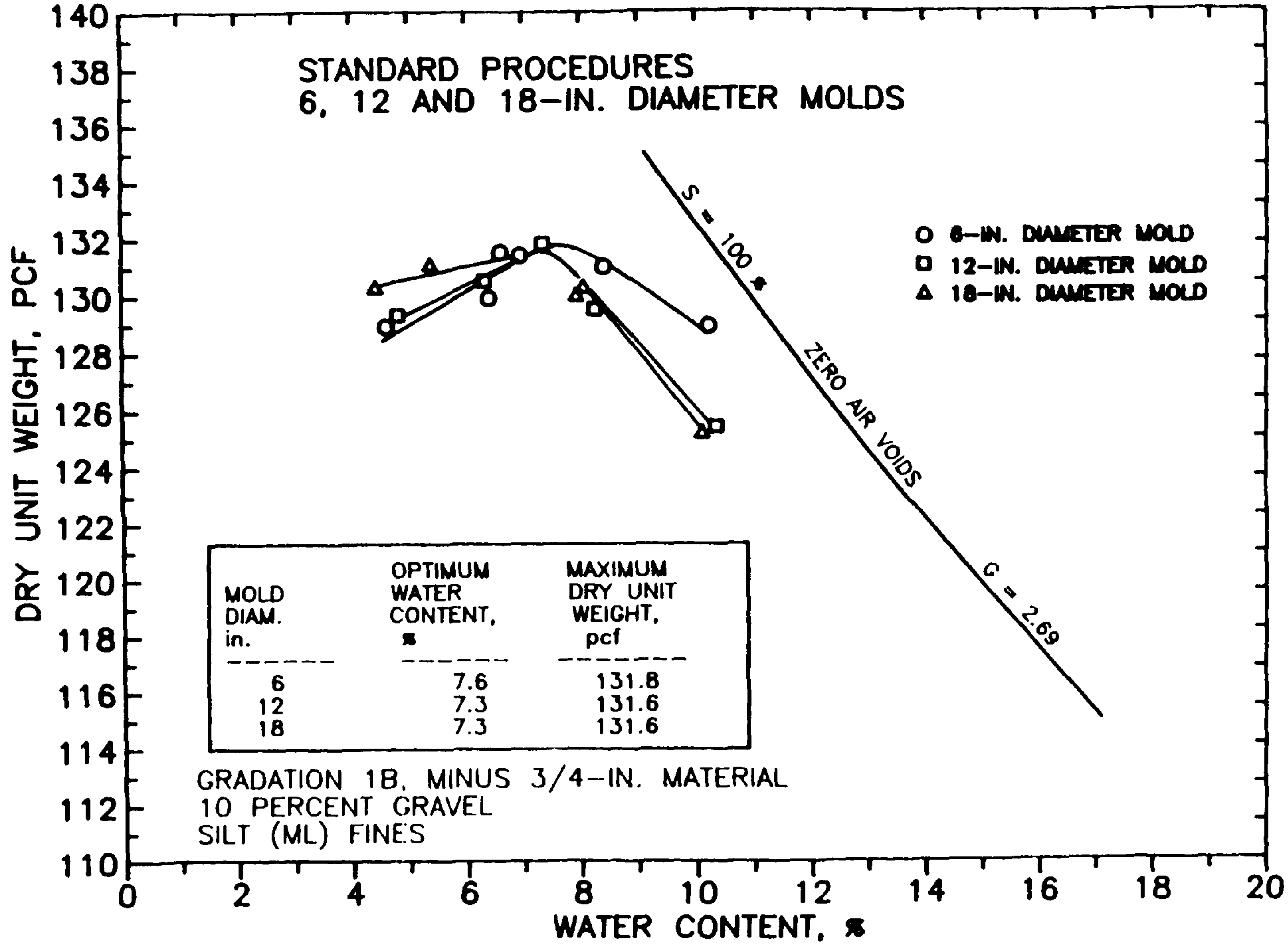


Figure 104. Compaction curves for tests performed on gradation No. 1B with silt (ML) fines in 6, 12, and 18-in. diameter molds to prove adequacy of proposed standard compaction procedures

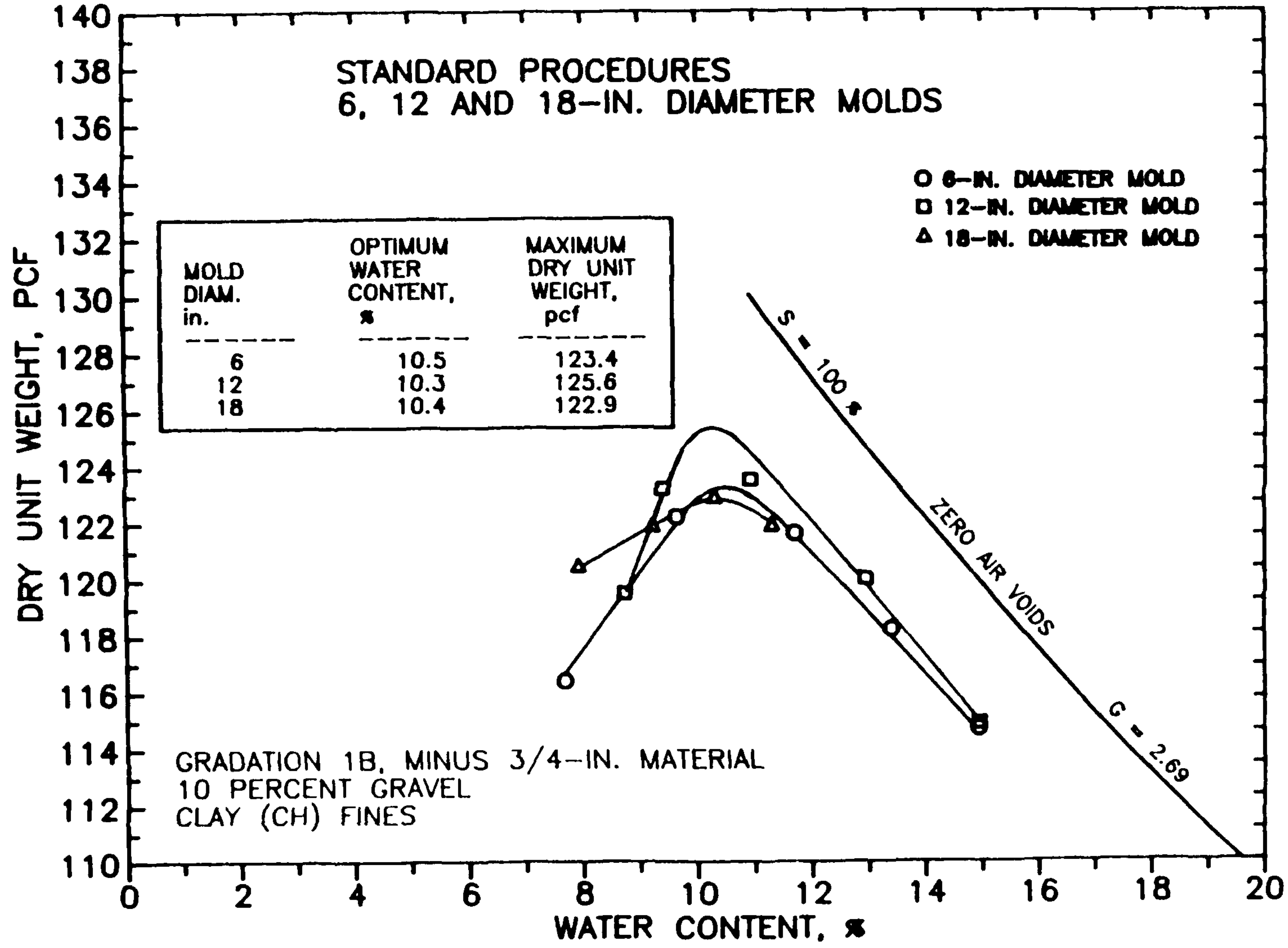


Figure 105. Compaction curves for tests performed on gradation No. 1B with clay (CH) fines in 6, 12, and 18-in. diameter molds to prove adequacy of proposed standard compaction procedures

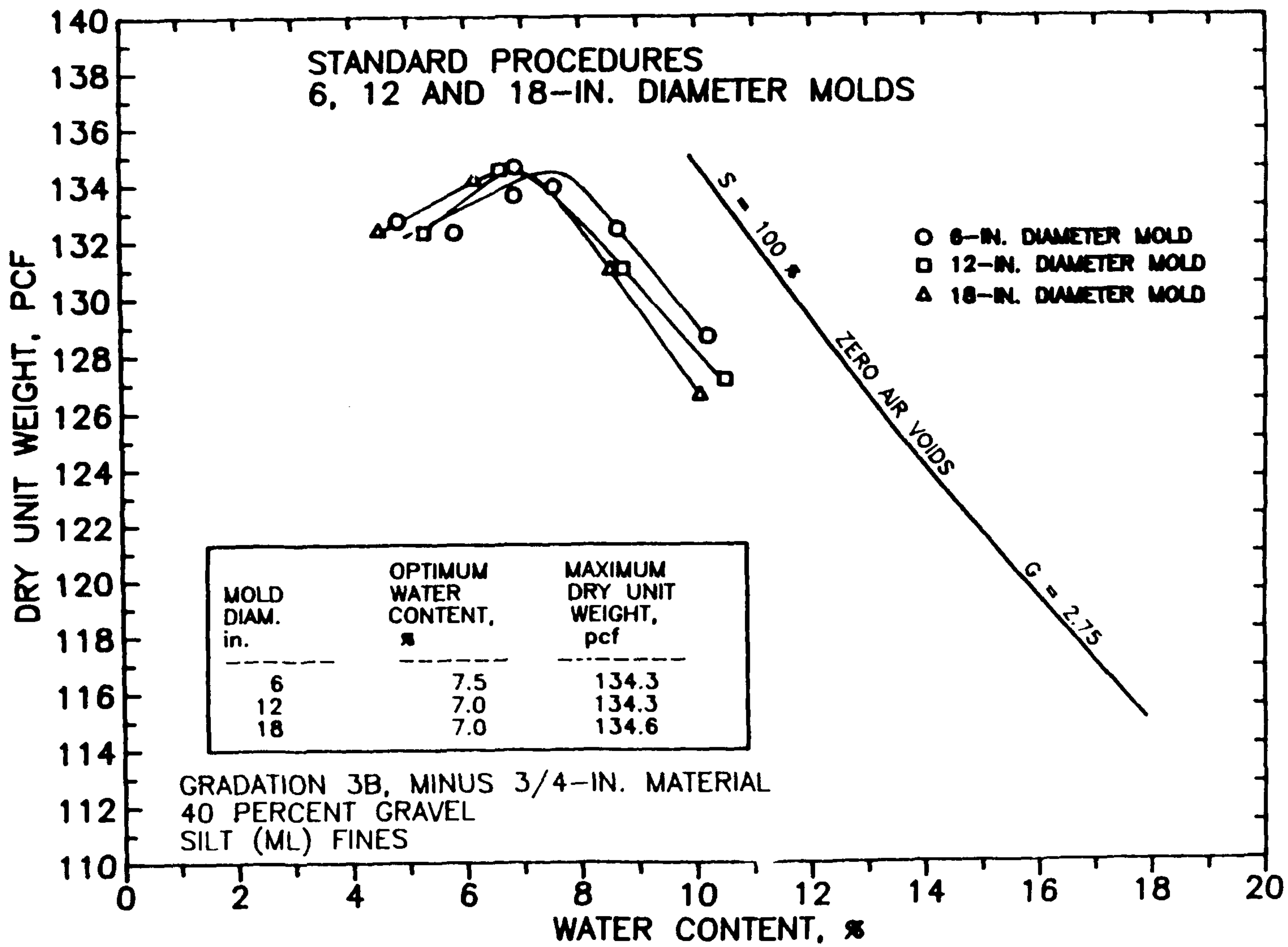


Figure 106. Compaction curves for tests performed on gradation No. 3B with silt (ML) fines in 6, 12, and 18-in. diameter molds to prove adequacy of proposed standard compaction procedures

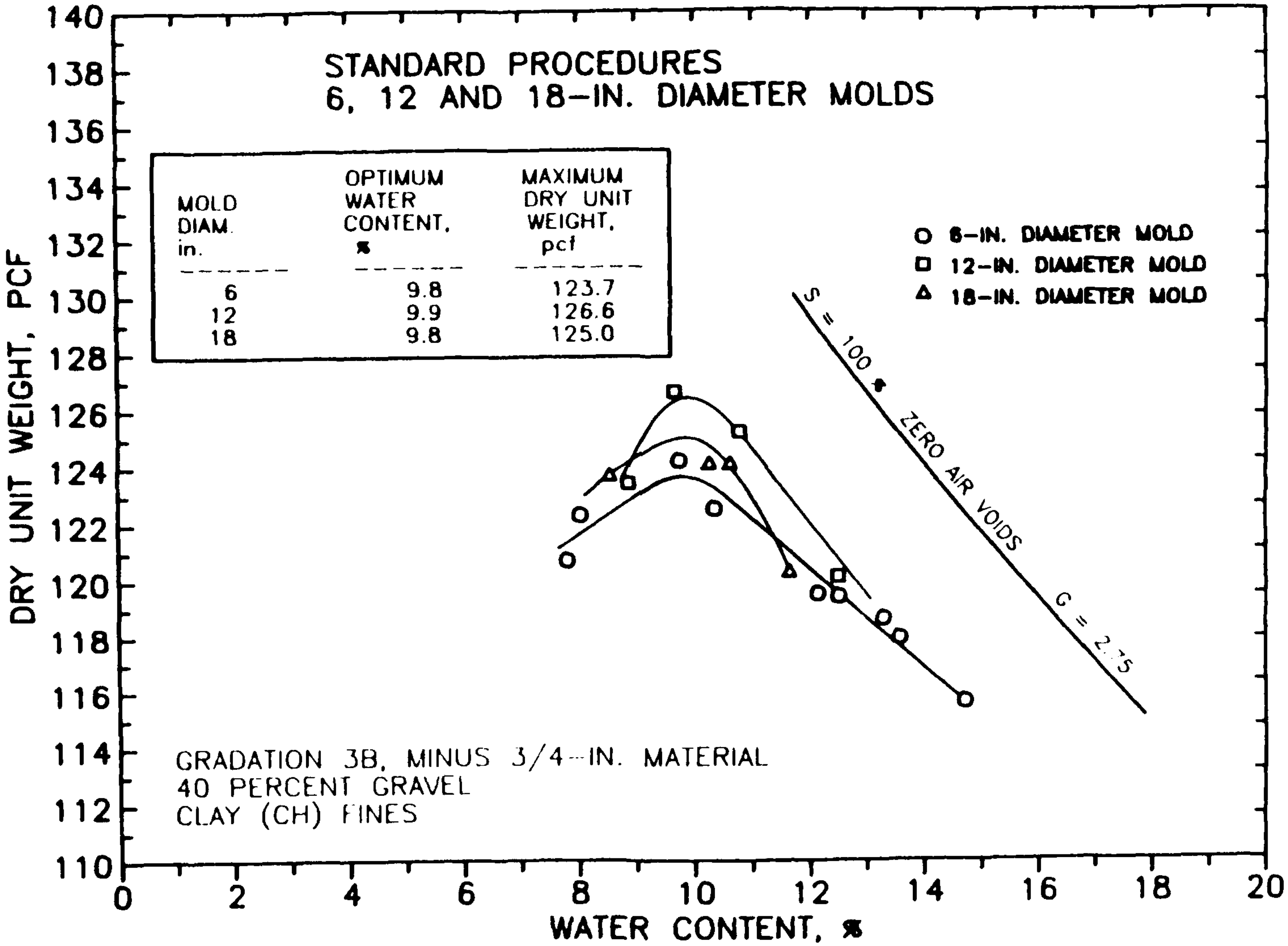


Figure 107. Compaction curves for tests performed on gradation No. 3B with clay (CH) fines in 6, 12, and 18-in. diameter molds to prove adequacy of proposed standard compaction procedures

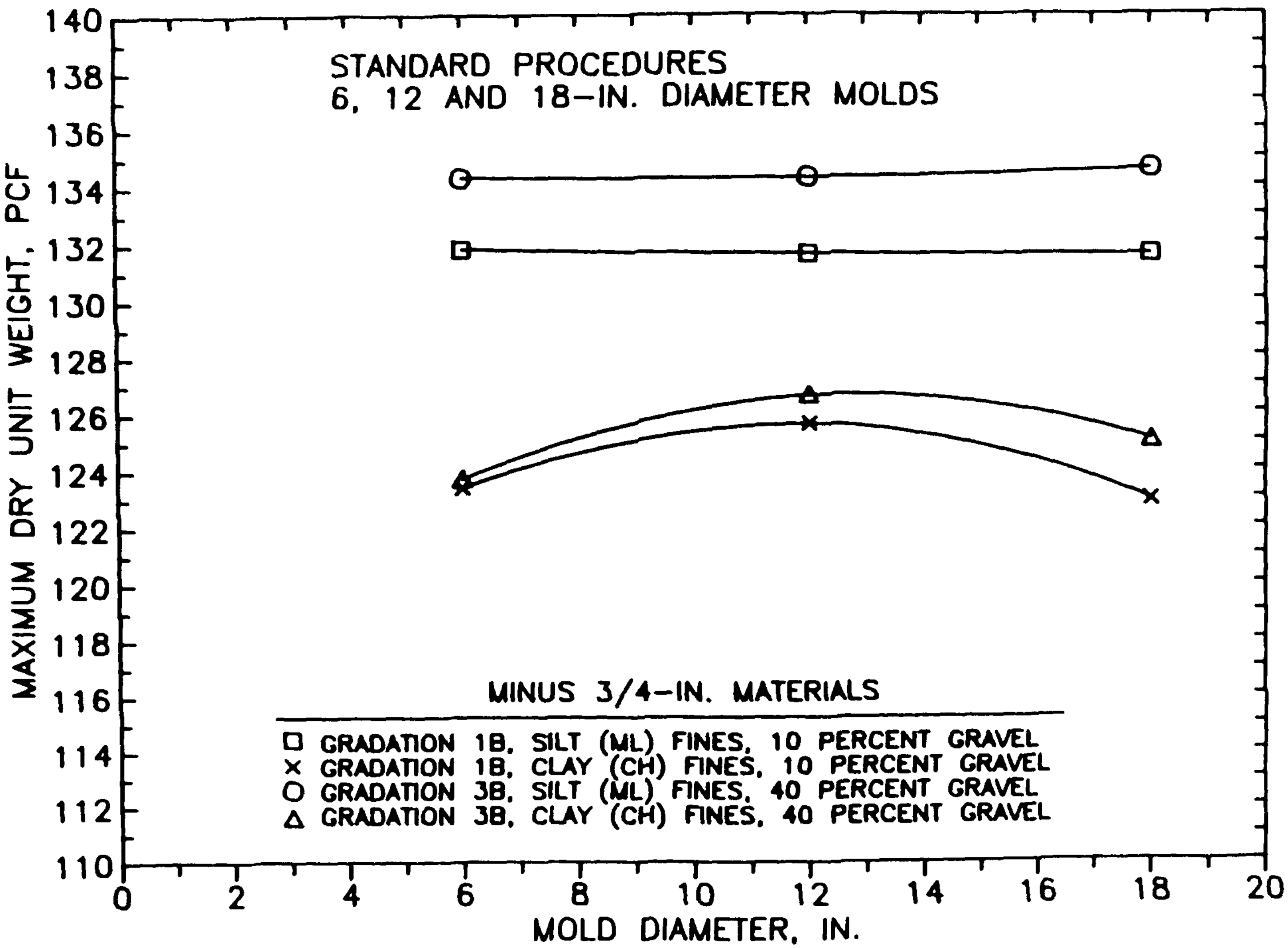


Figure 108. Maximum dry unit weight versus mold diameter resulting from proposed standard compaction procedures applied to gradation Nos. 1B and 3B

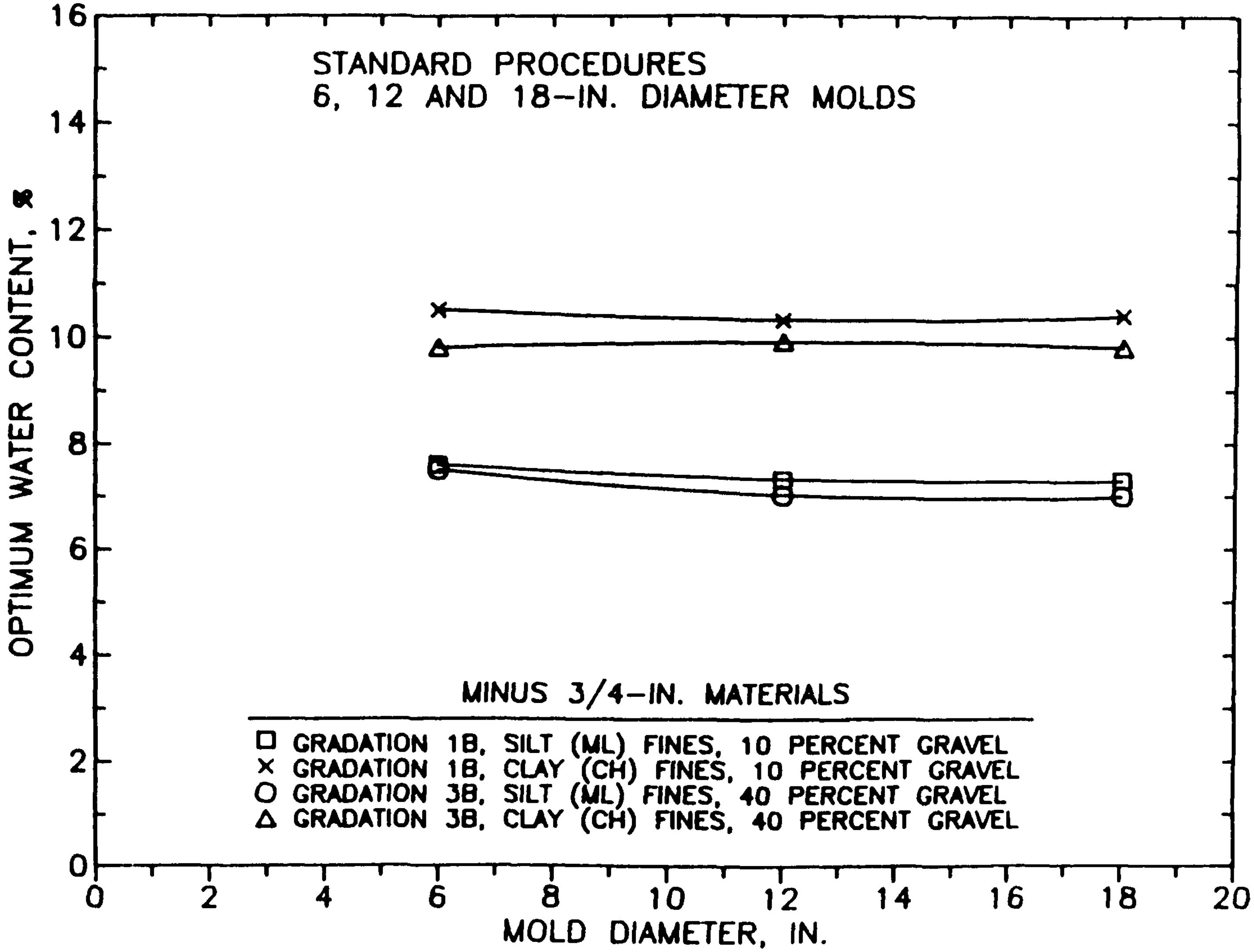


Figure 109   Optimum water content versus mold diameter resulting from proposed standard compaction procedures applied to gradation Nos. 1B and 3B

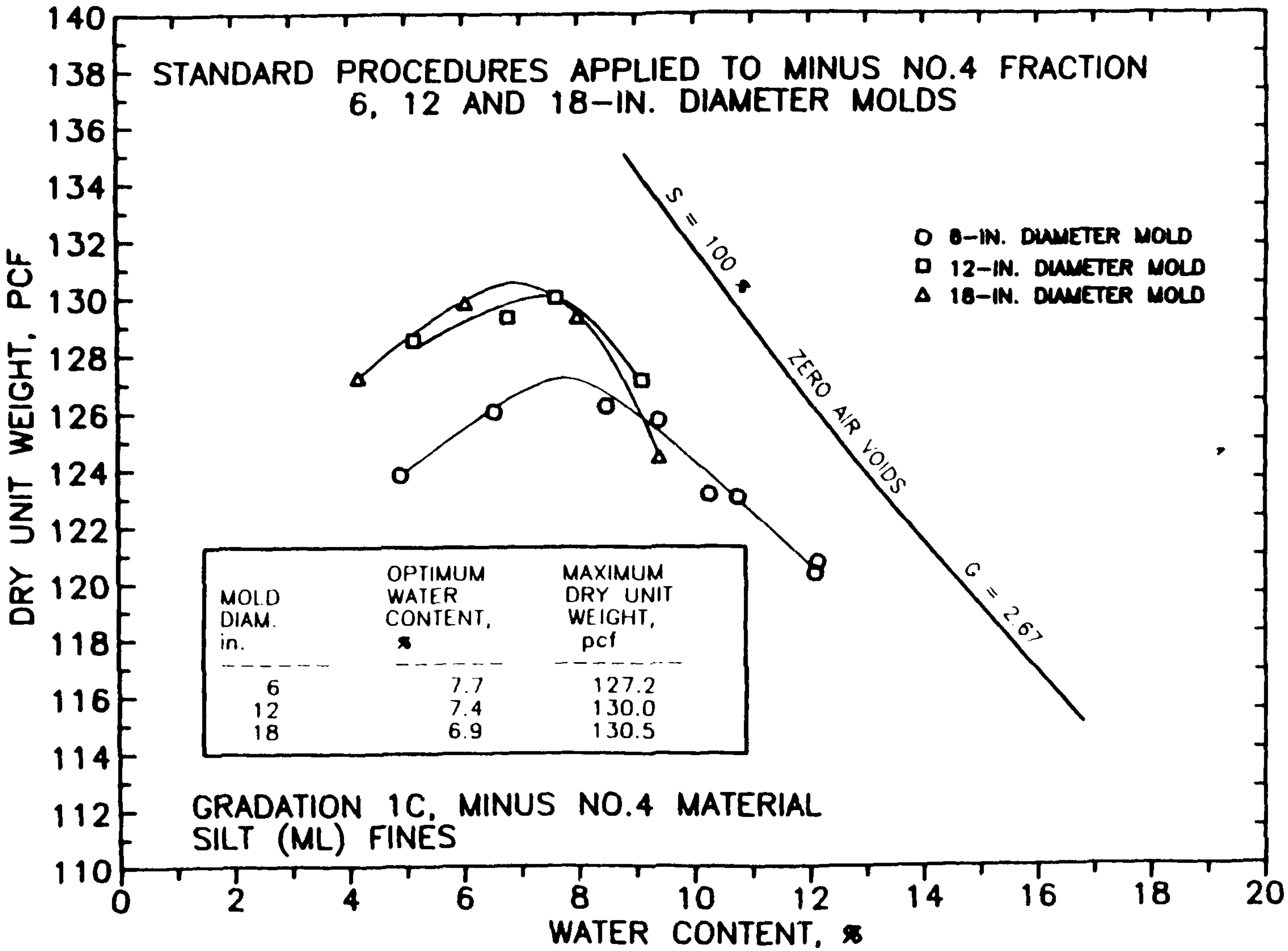


Figure 110. Compaction curves for tests performed on gradation No. 1C with silt (ML) fines in 6, 12, and 18-in. diameter molds using the adopted standard compaction procedures

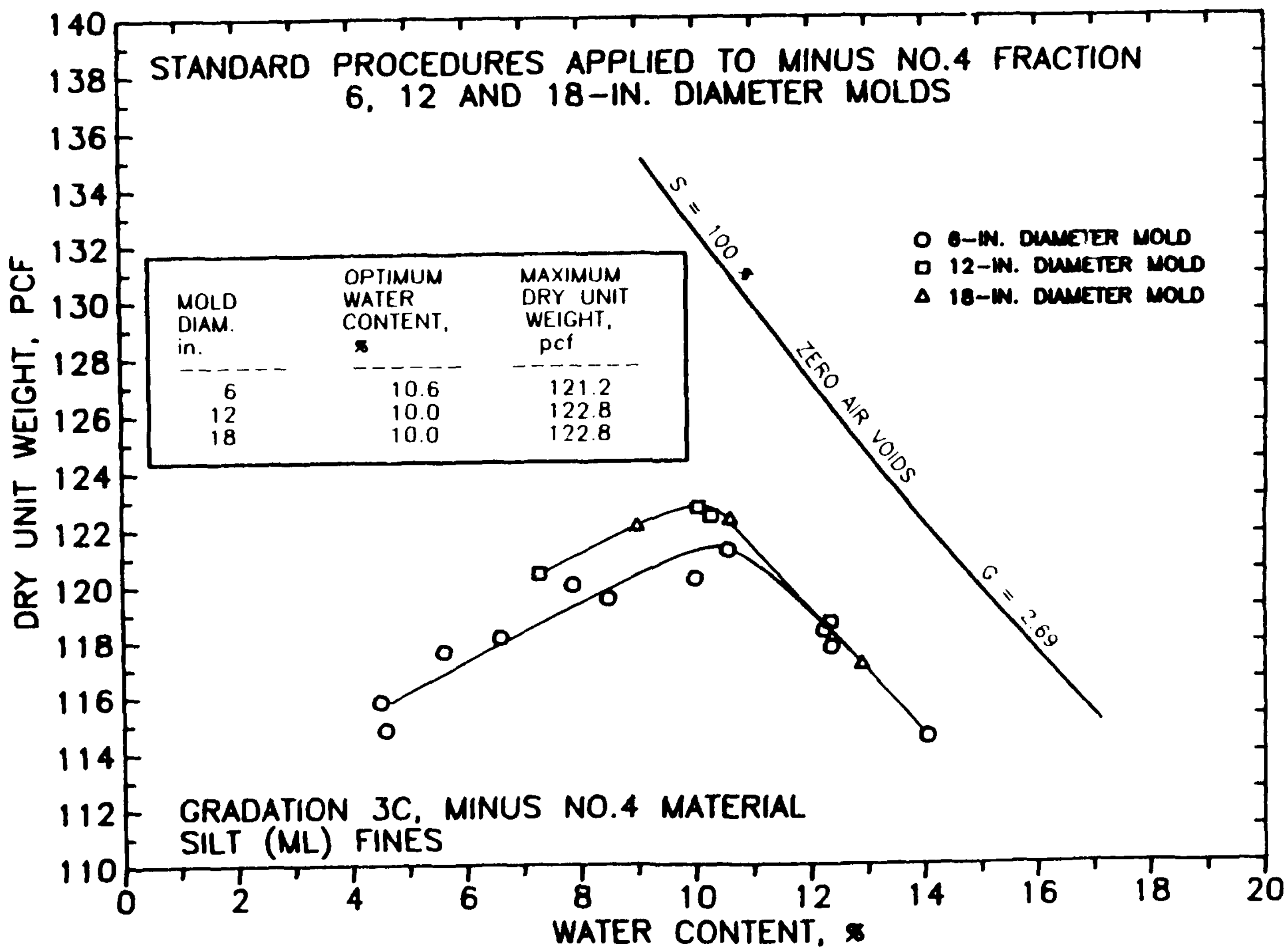


Figure 111. Compaction curves for tests performed on gradation No. 3C with silt (ML) fines in 6, 12, and 18-in. diameter molds using the adopted standard compaction procedures

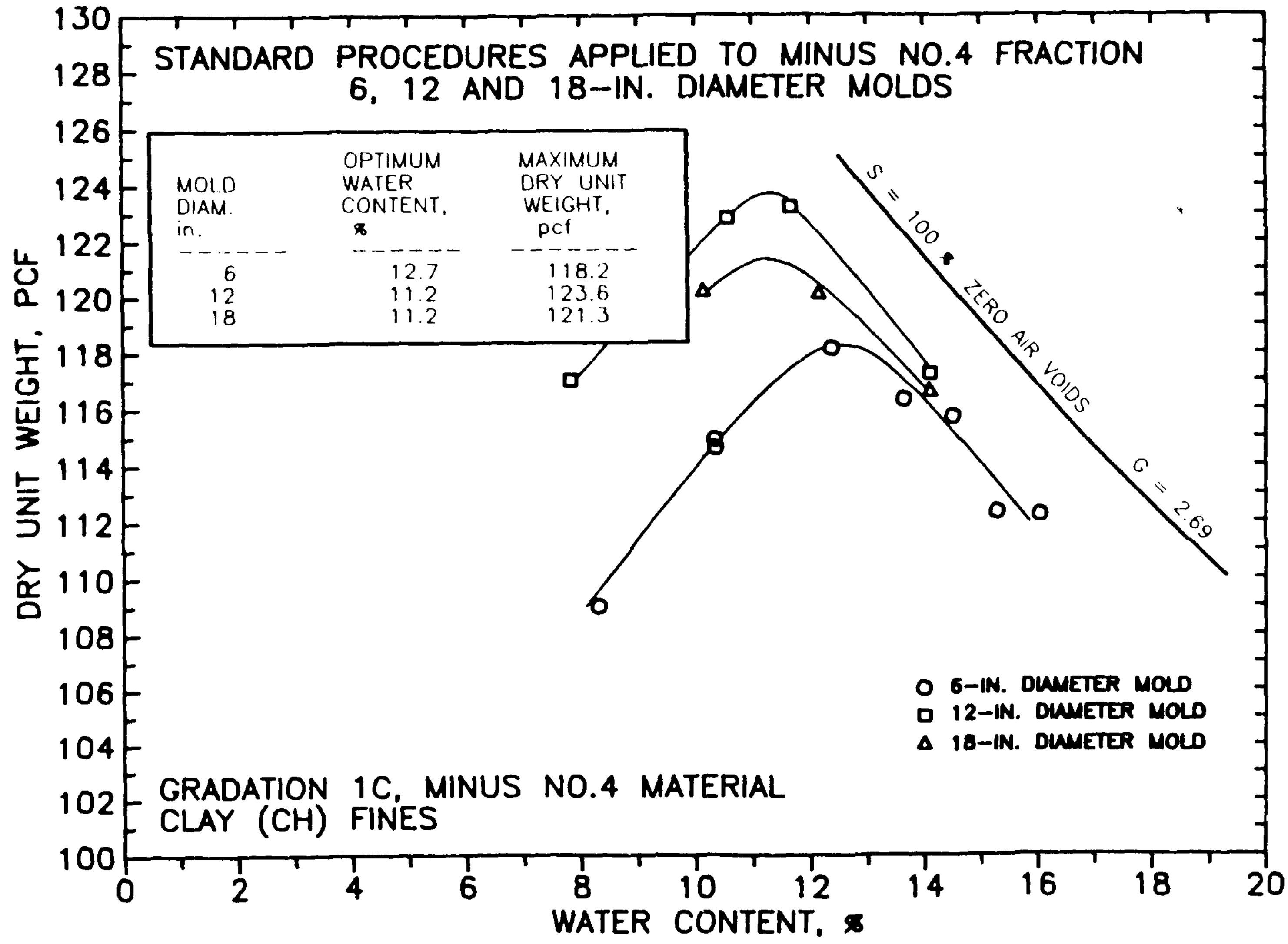


Figure 112. Compaction curves for tests performed on gradation No. 1C with clay (CH) fines in 6, 12, and 18-in. diameter molds using the adopted standard compaction procedures

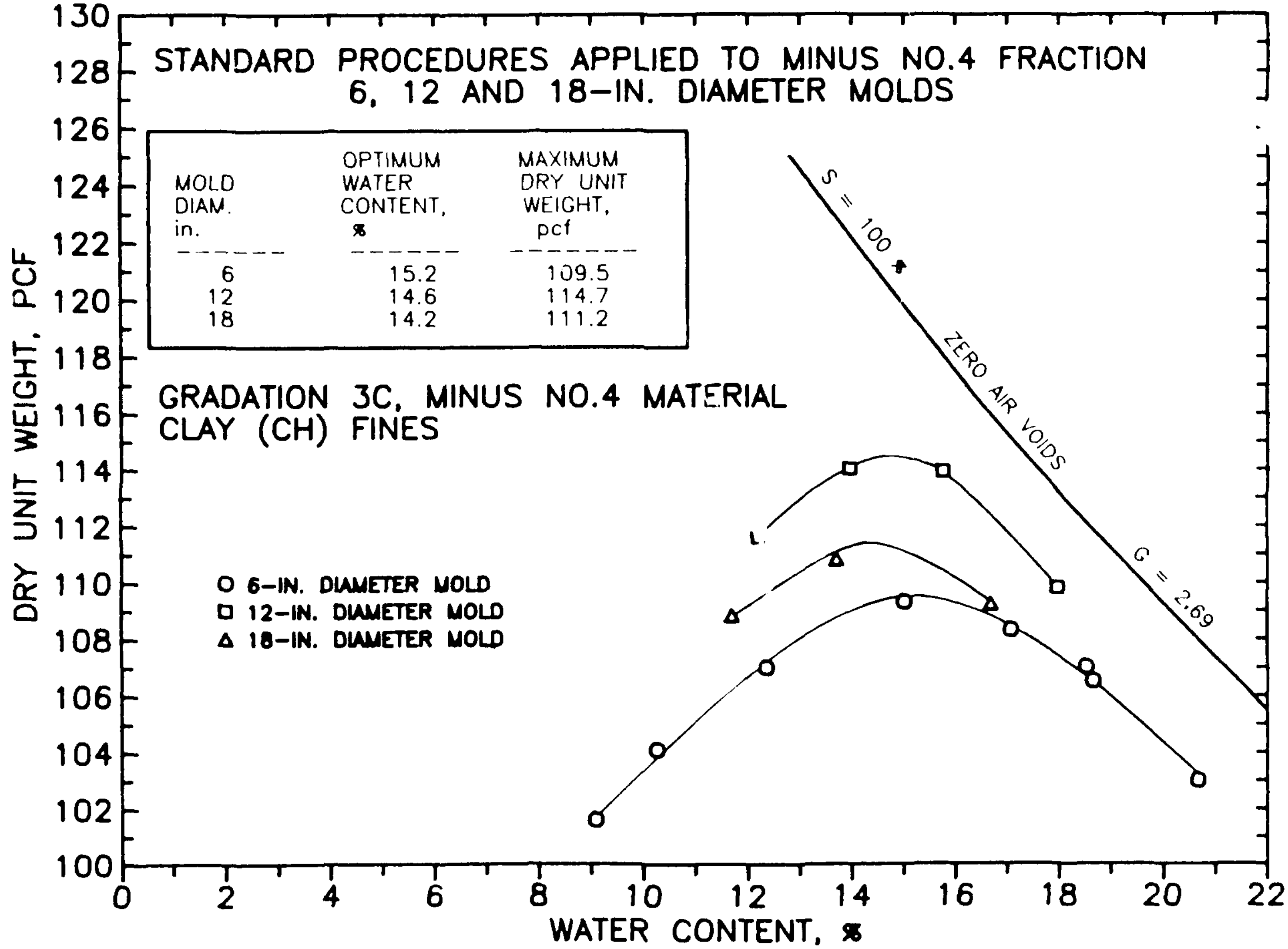


Figure 113. Compaction curves for tests performed on gradation No. 3C with clay (CH) fines in 6, 12, and 18-in. diameter molds using the adopted standard compaction procedures

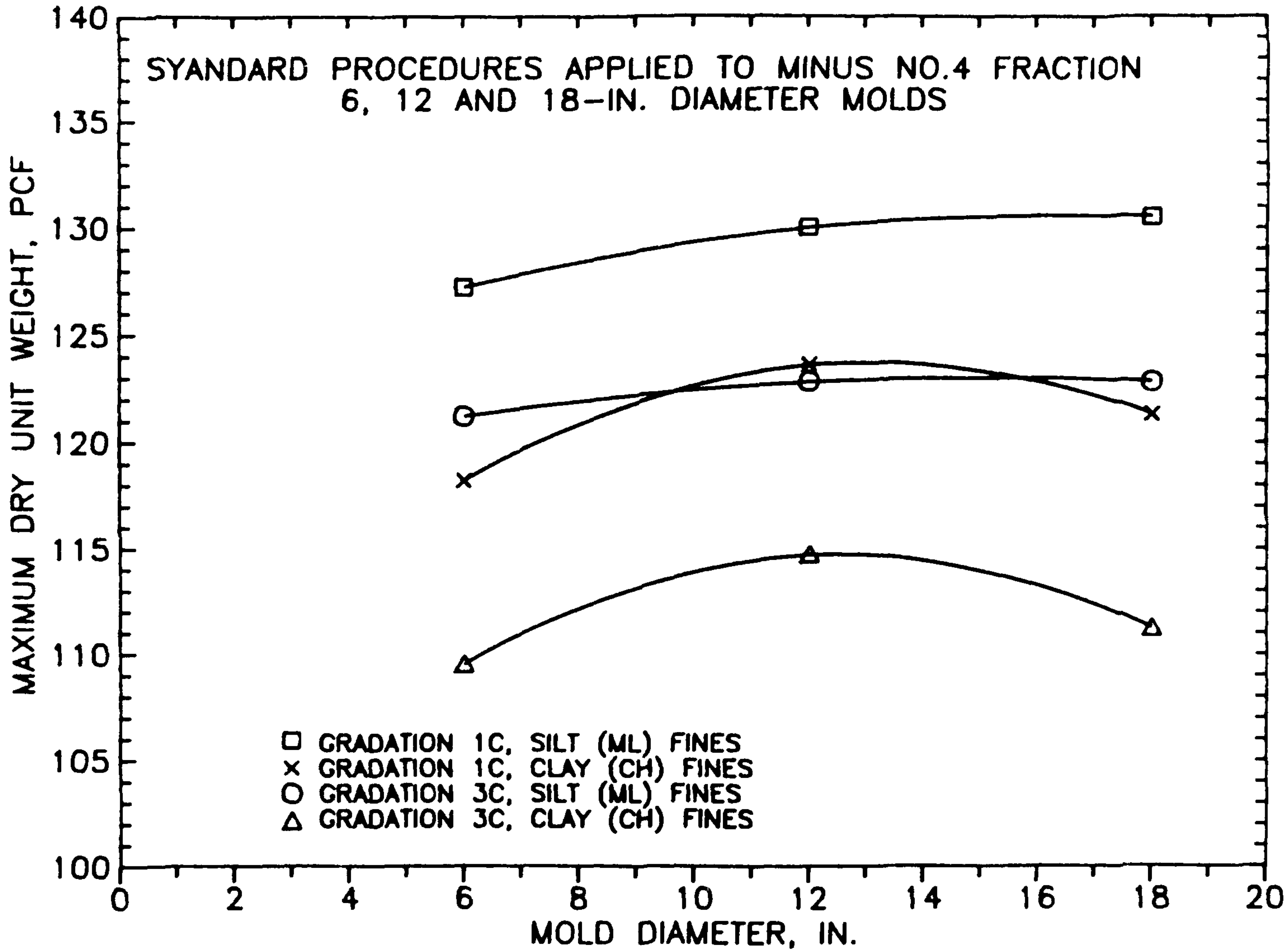


Figure 114. Maximum dry unit weight versus mold diameter resulting from adopted standard compaction procedures applied to gradation Nos. 1C and 3C

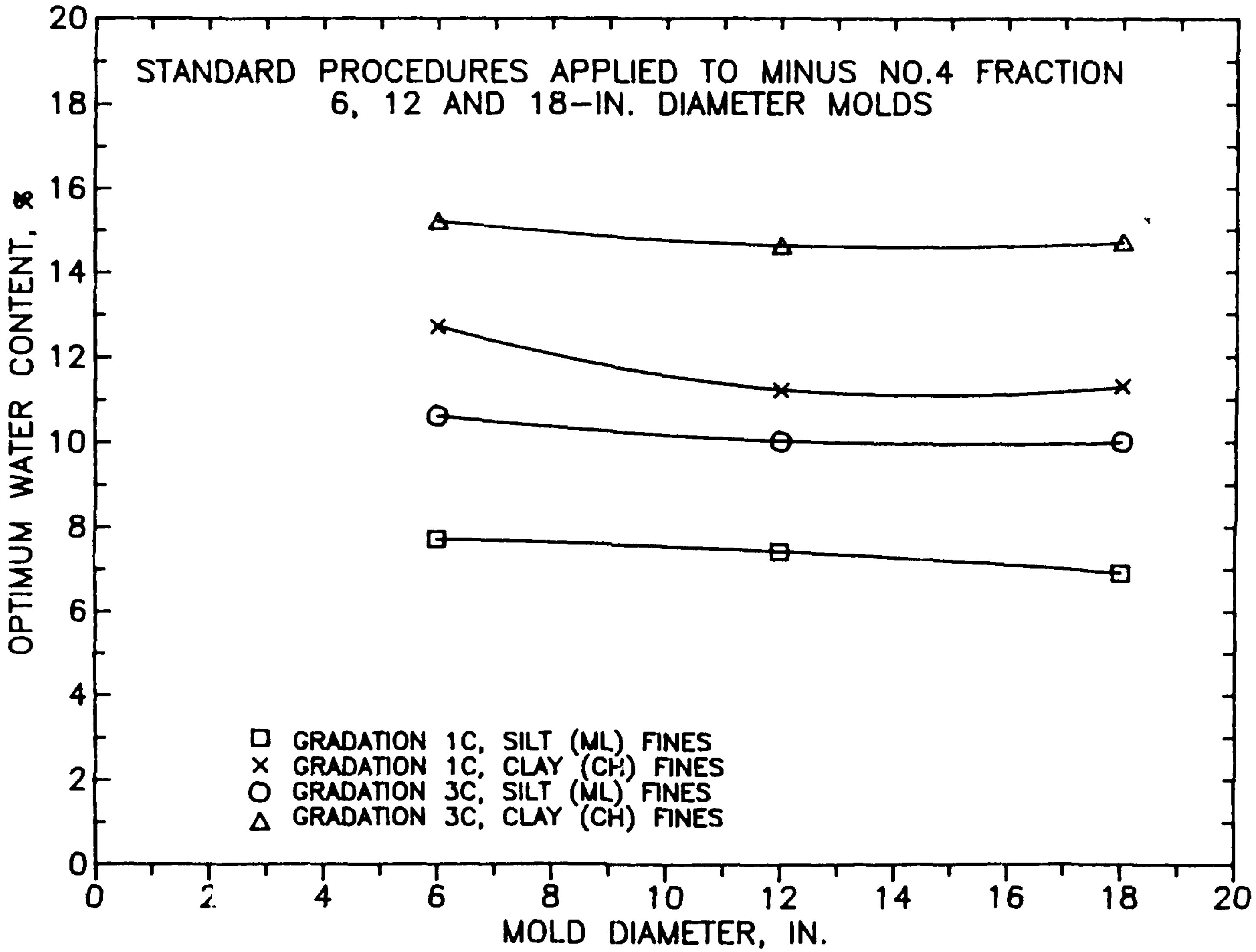


Figure 115. Optimum water content versus mold diameter resulting from adopted standard compaction procedures applied to gradation Nos. 1C and 3C

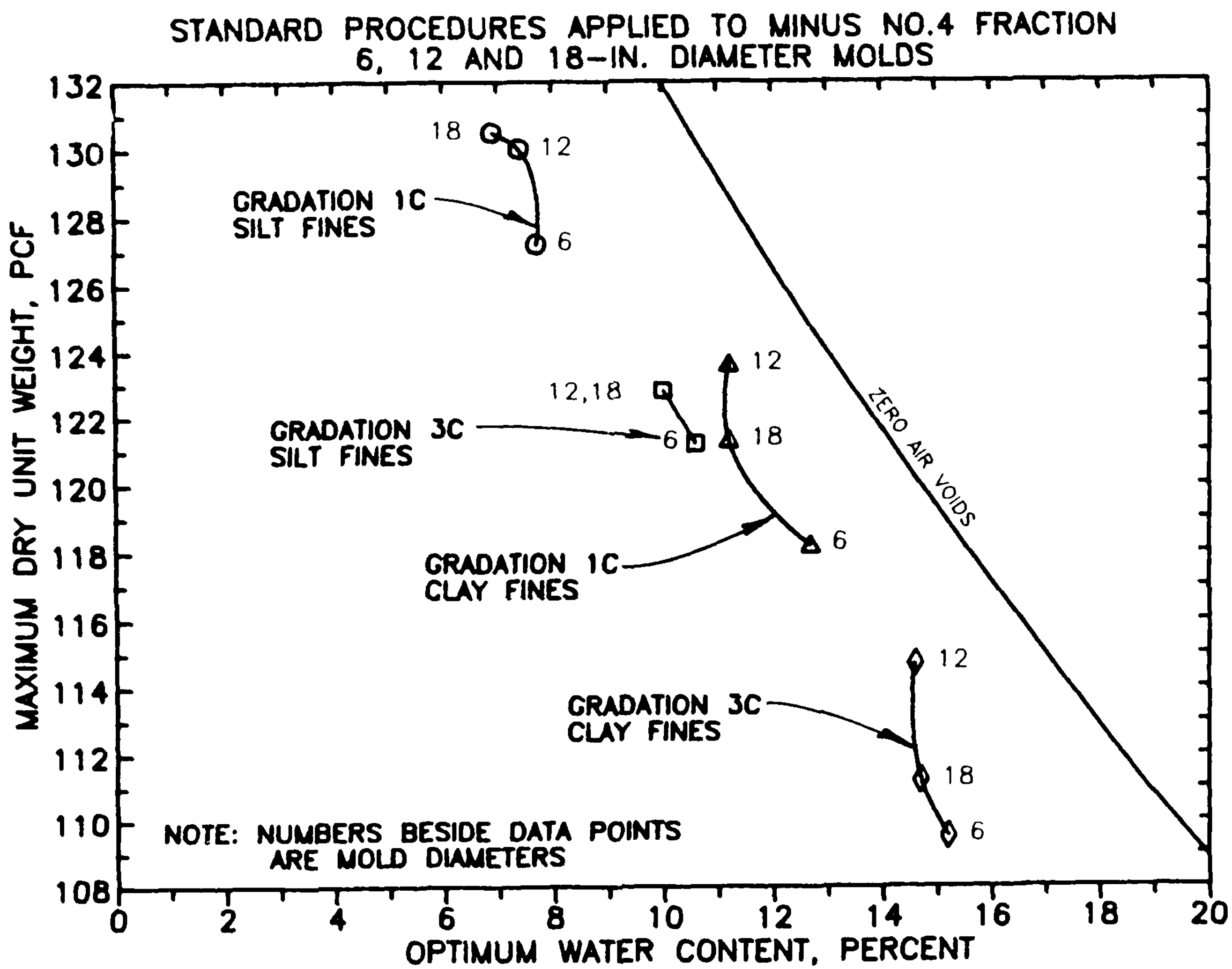


Figure 116. Maximum dry unit weights versus optimum water contents from adopted standard compaction procedures applied to gradation Nos. 1C and 3C

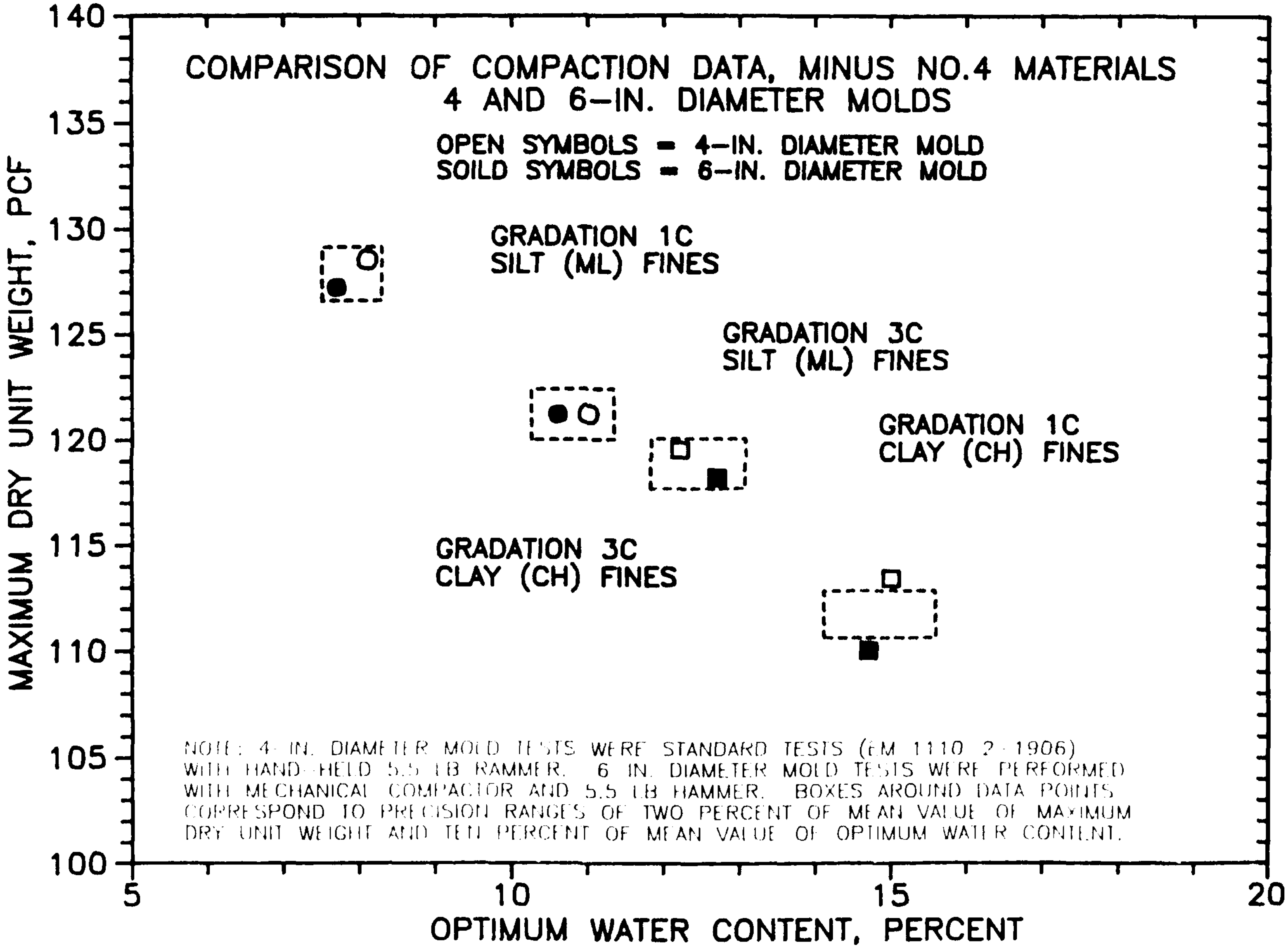


Figure 117. Comparison of compaction data for the minus No.4 fractions obtained in the 4- and 6-in. diameter molds.

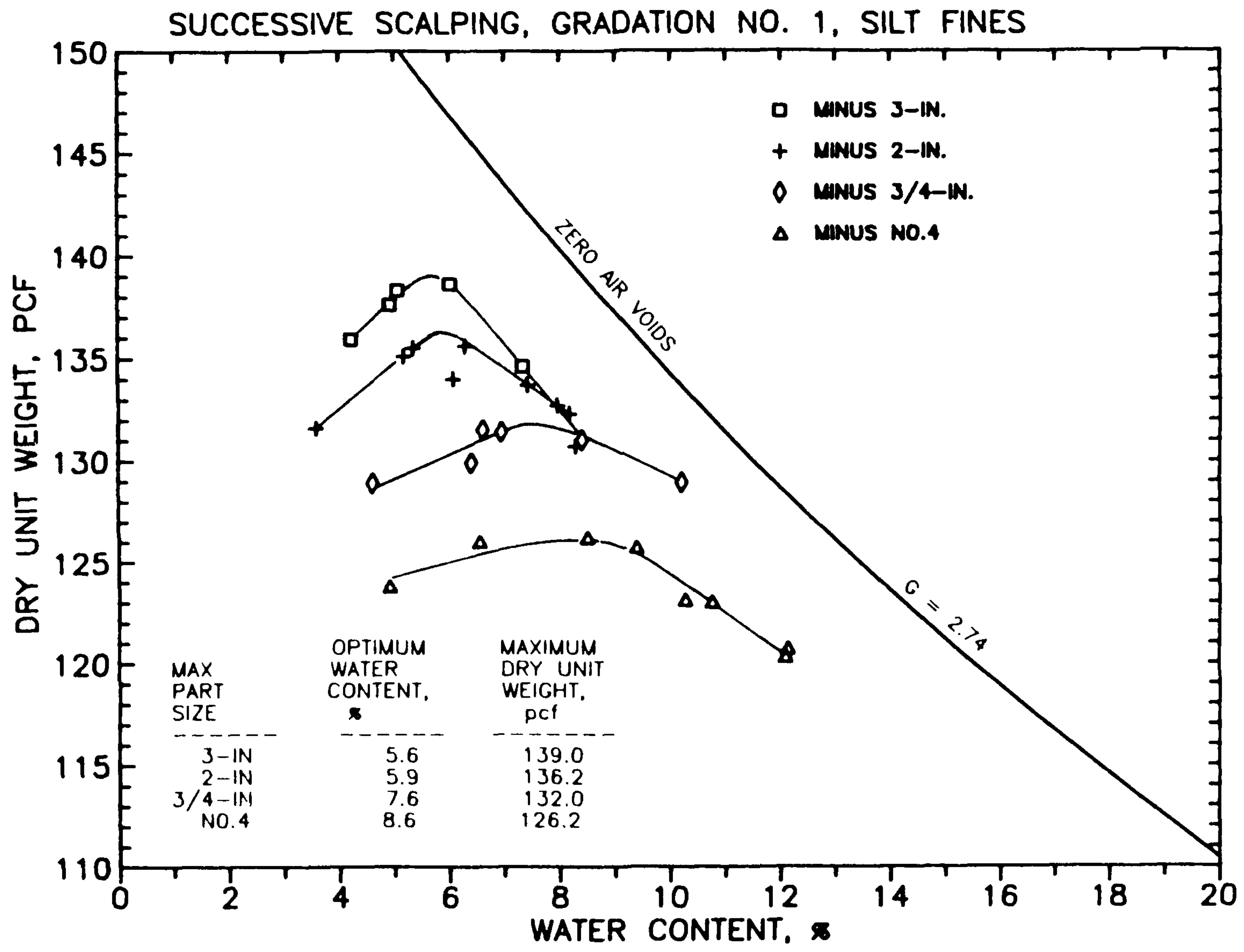


Figure 118. Compaction curves for gradation No. 1 with silt (ML) fines and its associated fractions

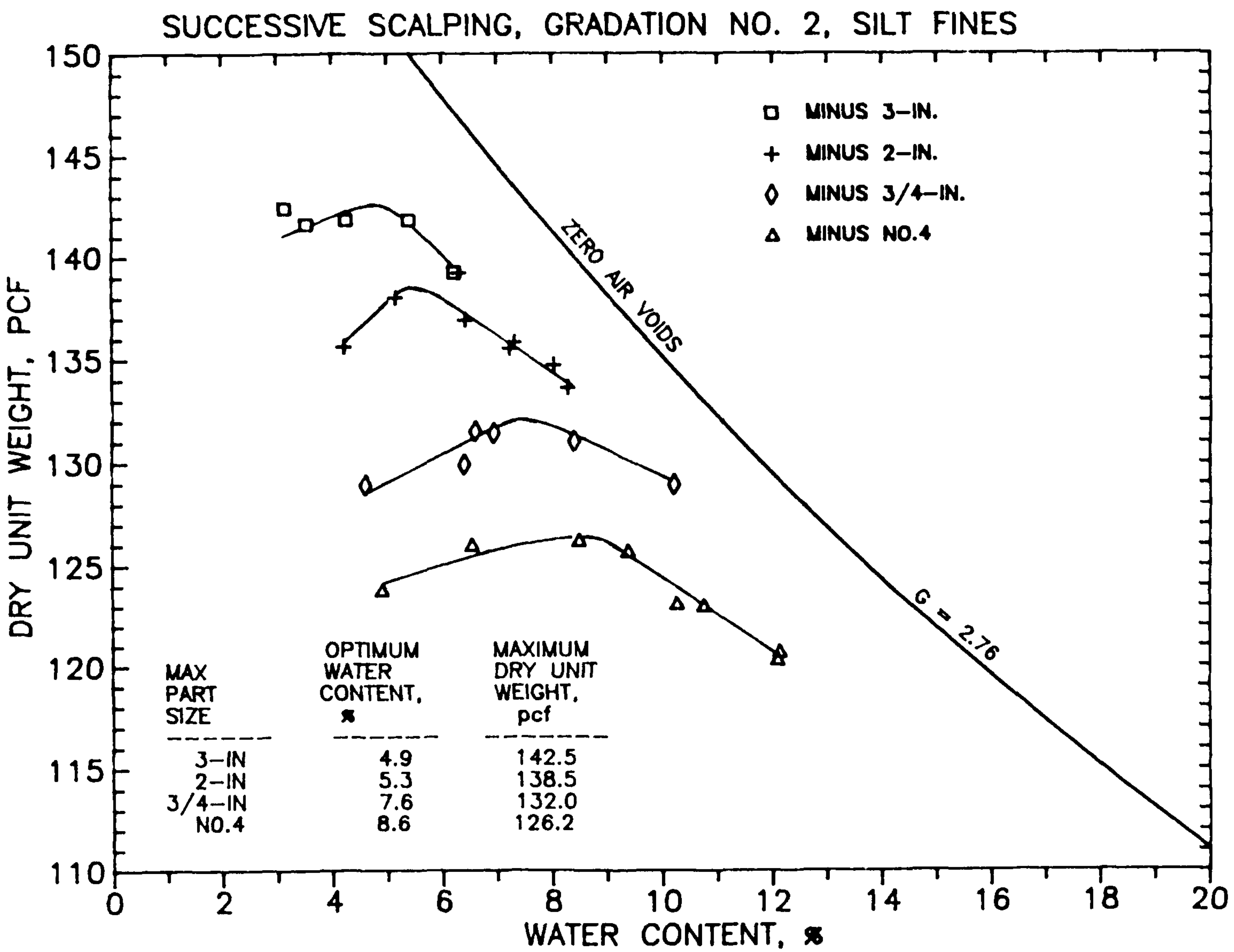


Figure 119. Compaction curves for gradation No. 2 with silt (ML) fines and its associated fractions

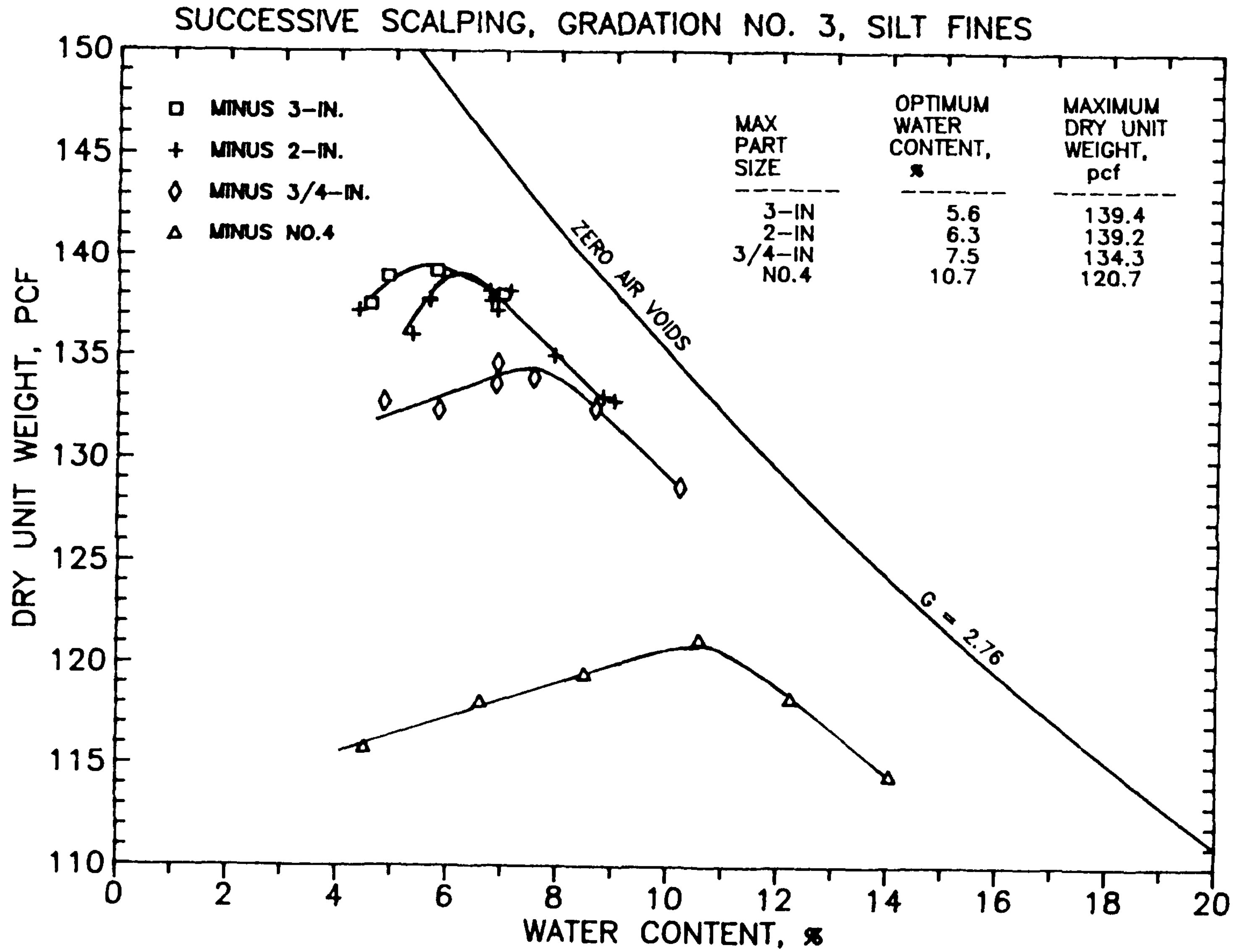


Figure 120. Compaction curves for gradation No. 3 with silt (ML) fines and its associated fractions

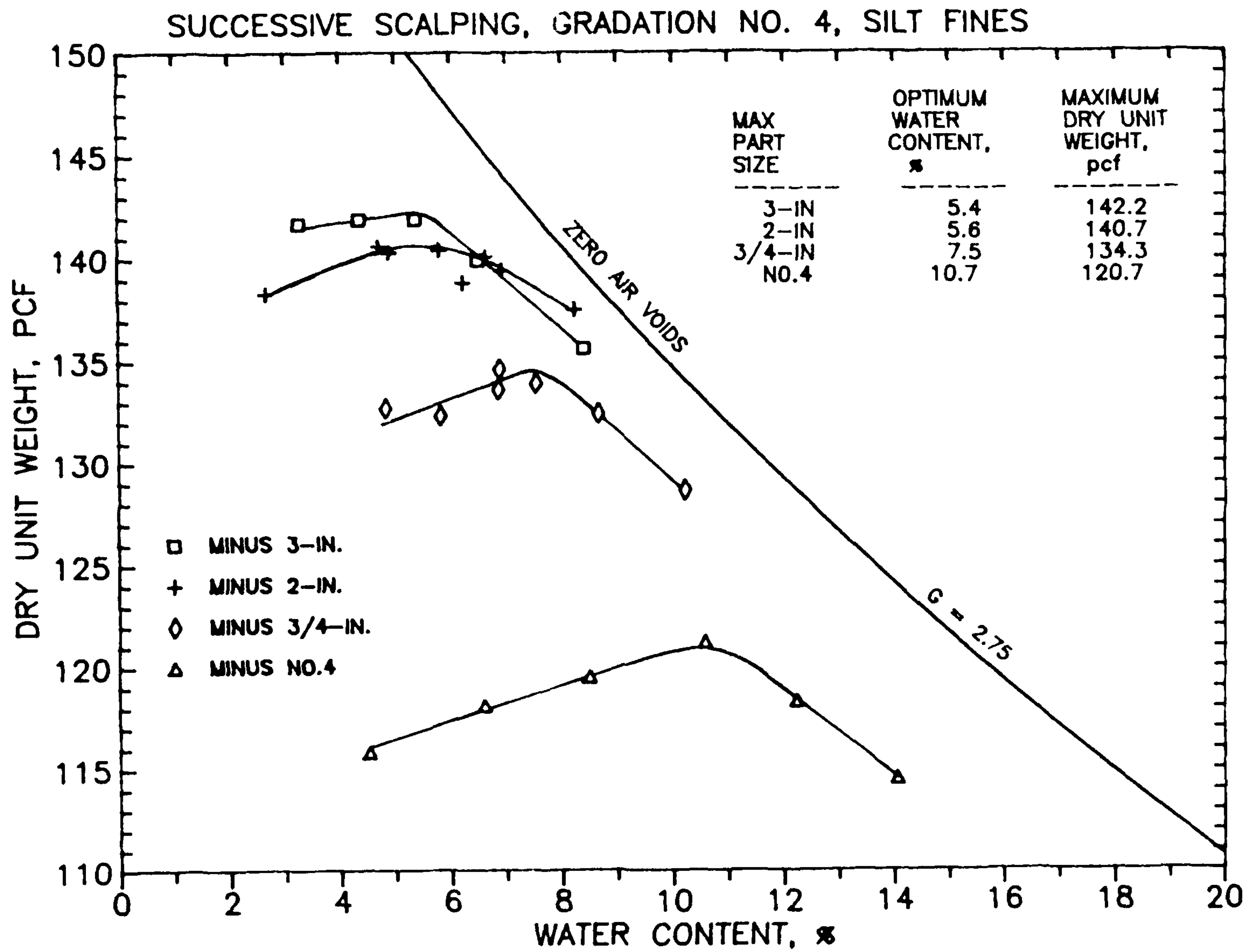


Figure 121. Compaction curves for gradation No. 4 with silt (ML) fines and its associated fractions

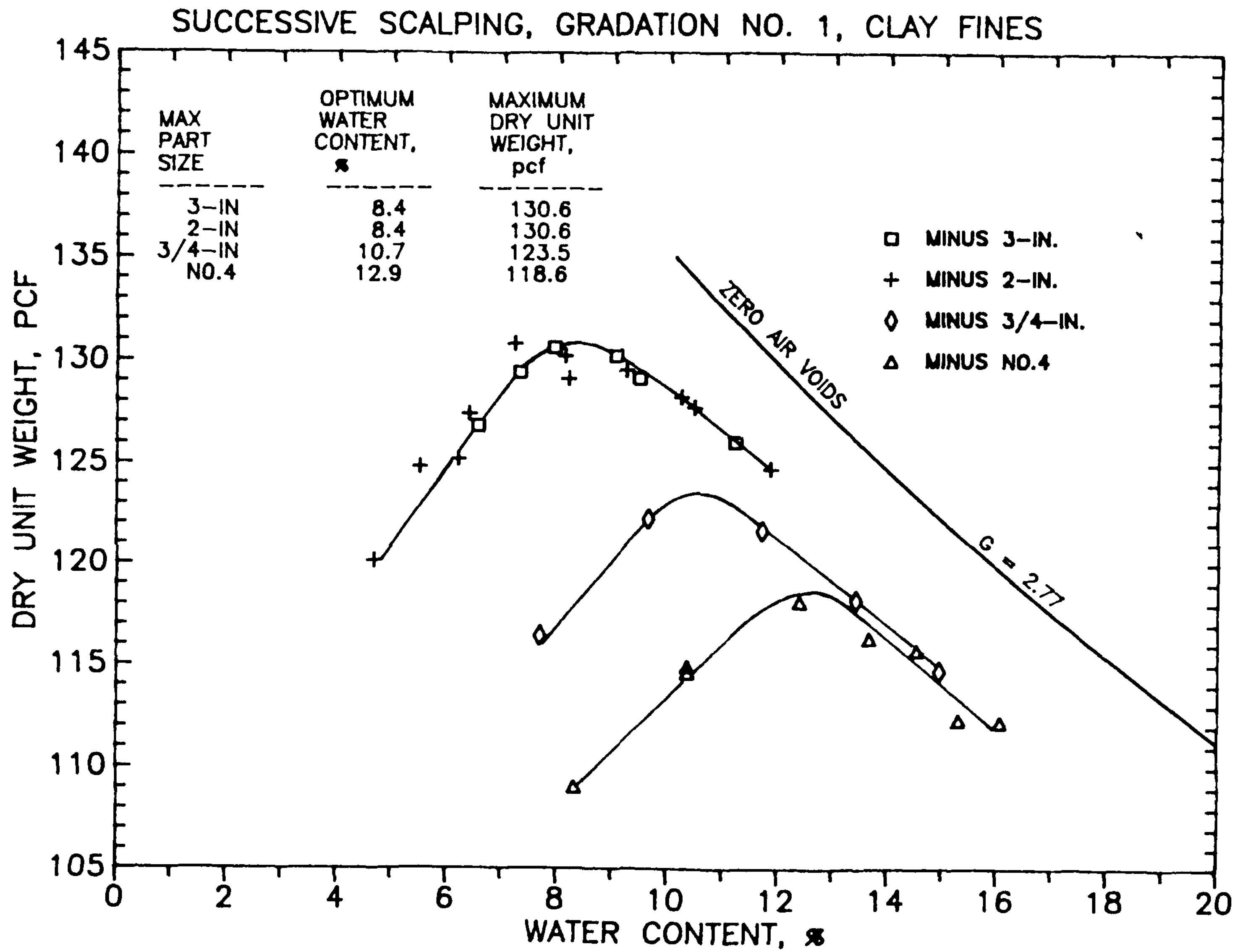


Figure 122. Compaction curves for gradation No. 1 with clay (CH) fines and its associated fractions

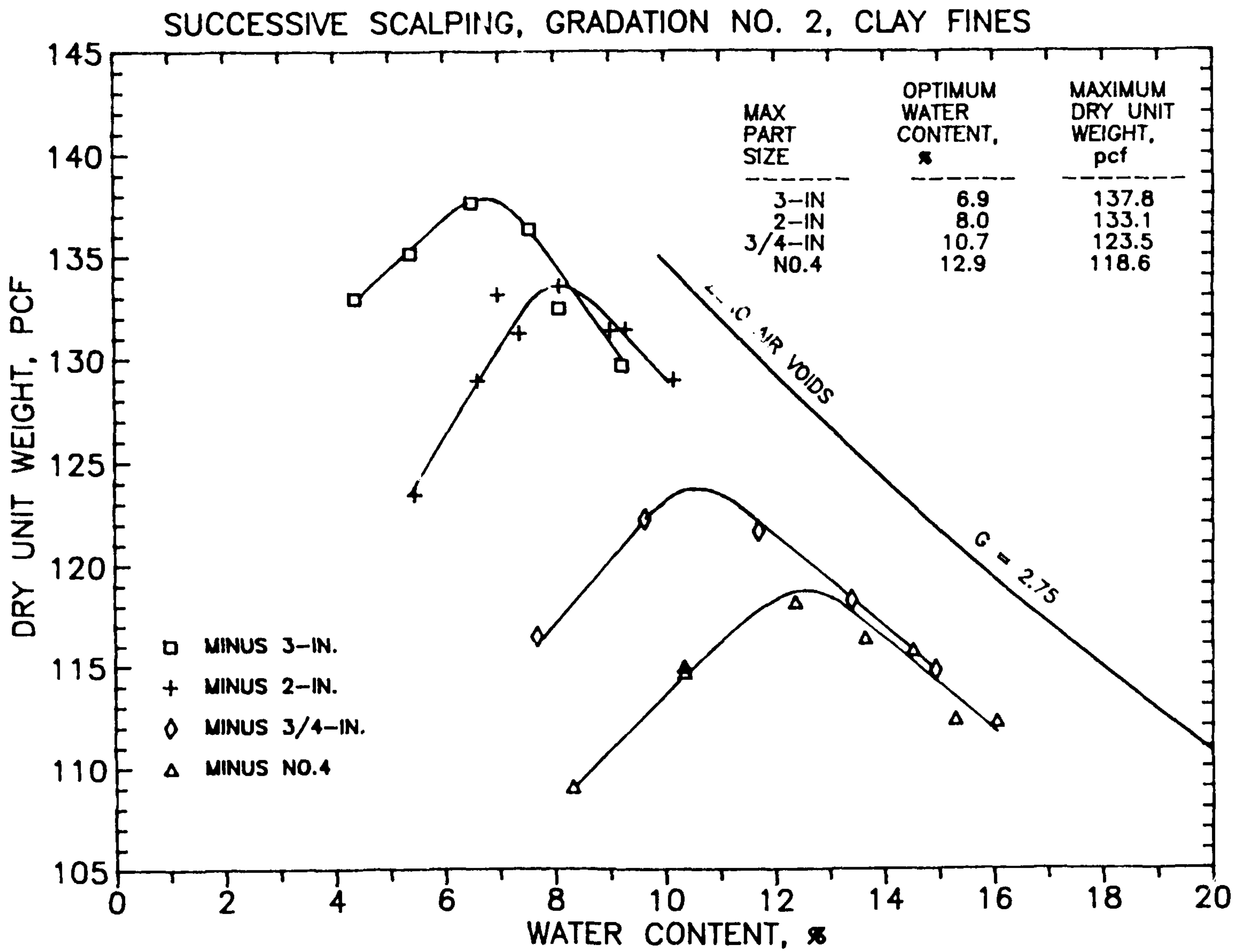


Figure 123. Compaction curves for gradation No. 2 with clay (CH) fines and its associated fractions

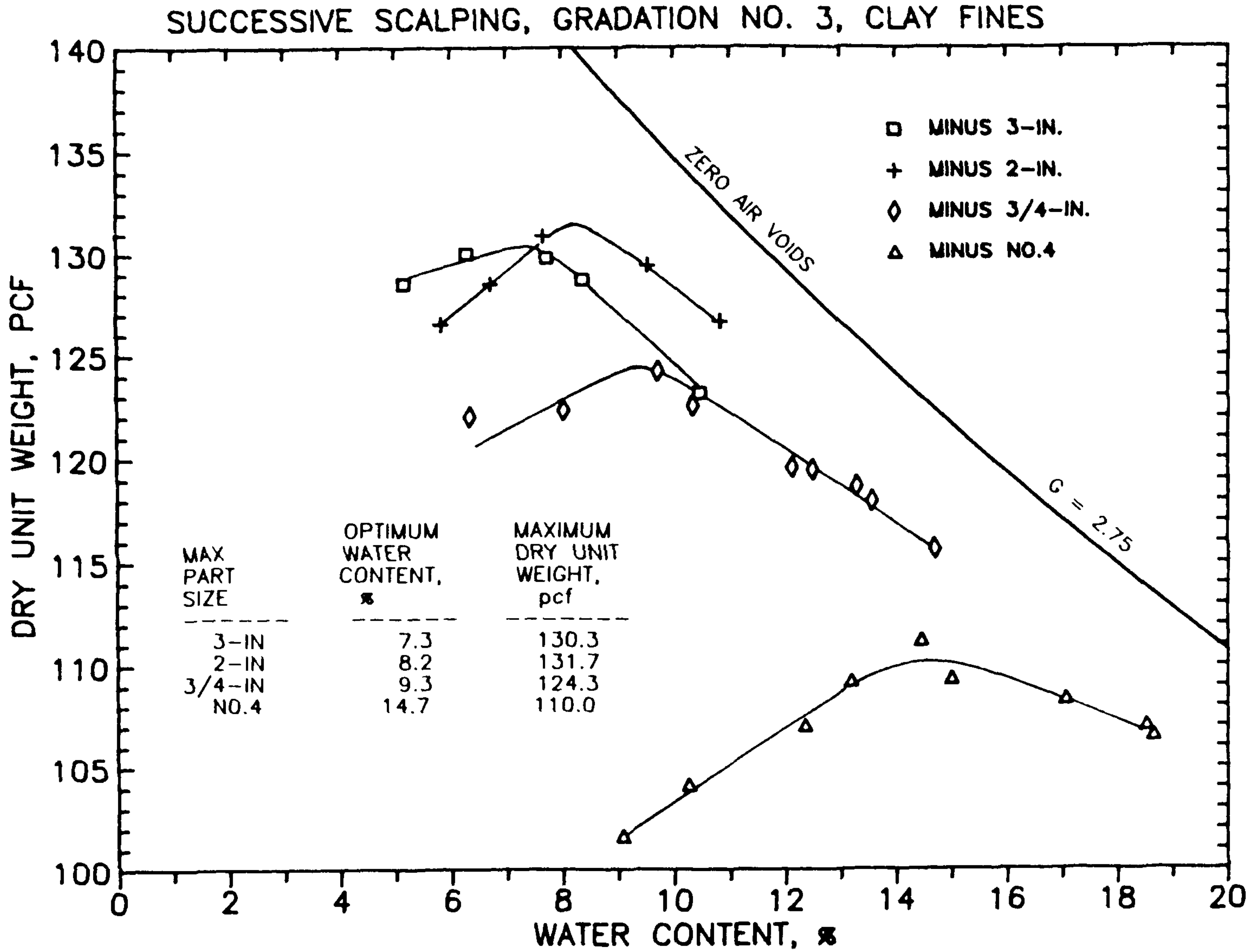


Figure 124. Compaction curves for gradation No. 3 with clay (CH) fines and its associated fractions

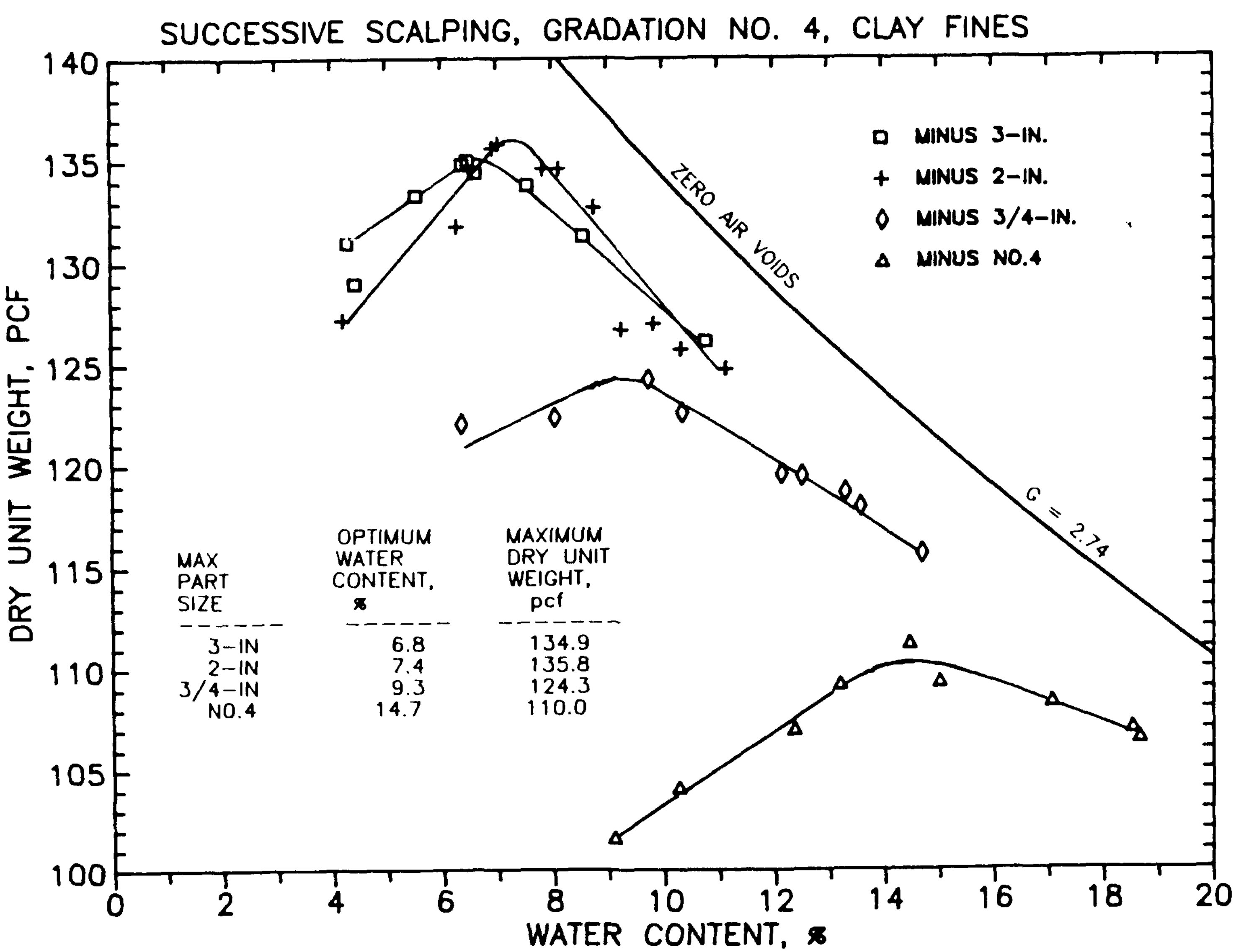


Figure 125. Compaction curves for gradation No. 4 with clay (CH) fines and its associated fractions

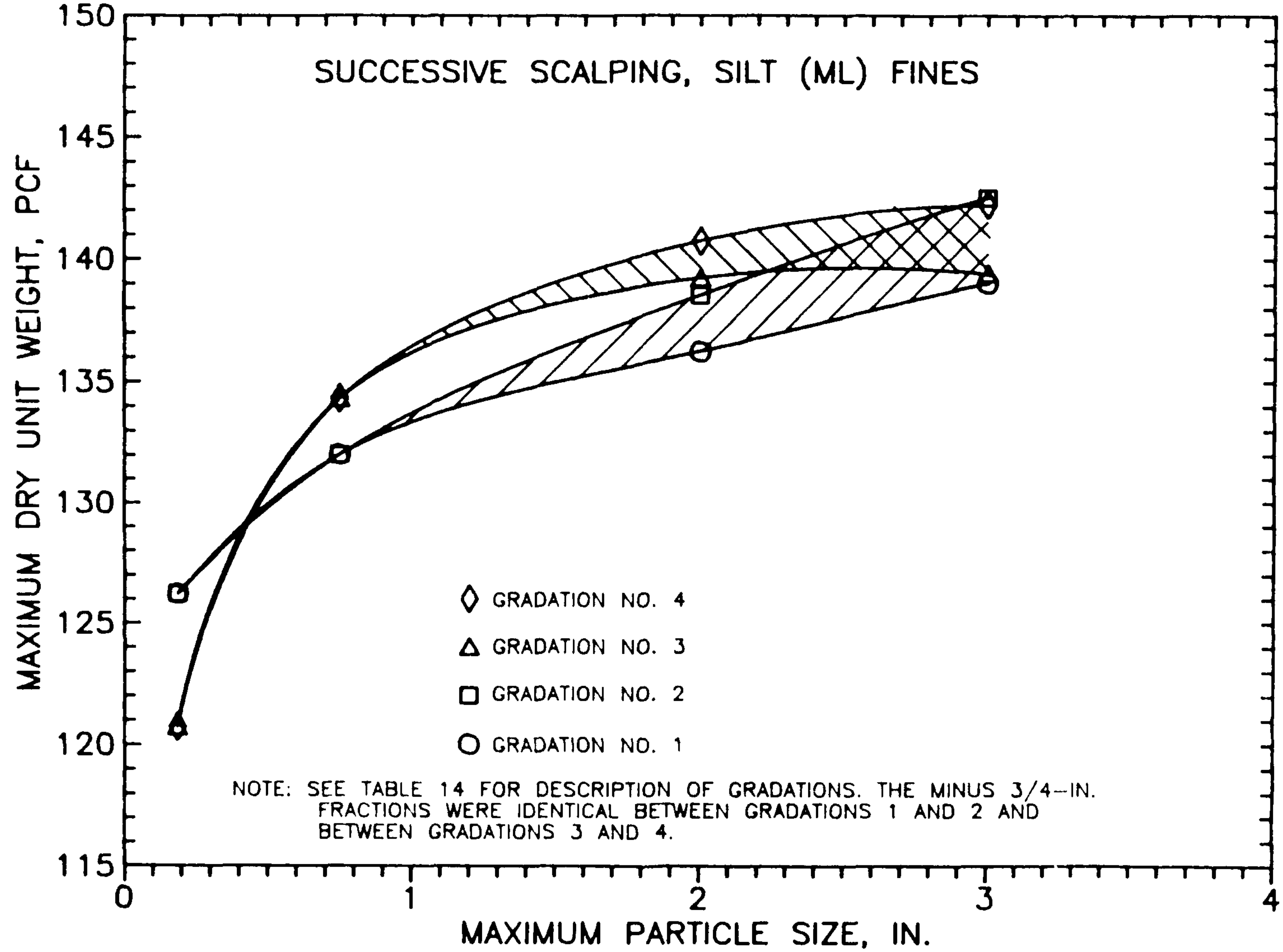


Figure 126. Maximum dry unit weight versus maximum particle size, all test gradations with silt (ML) fines

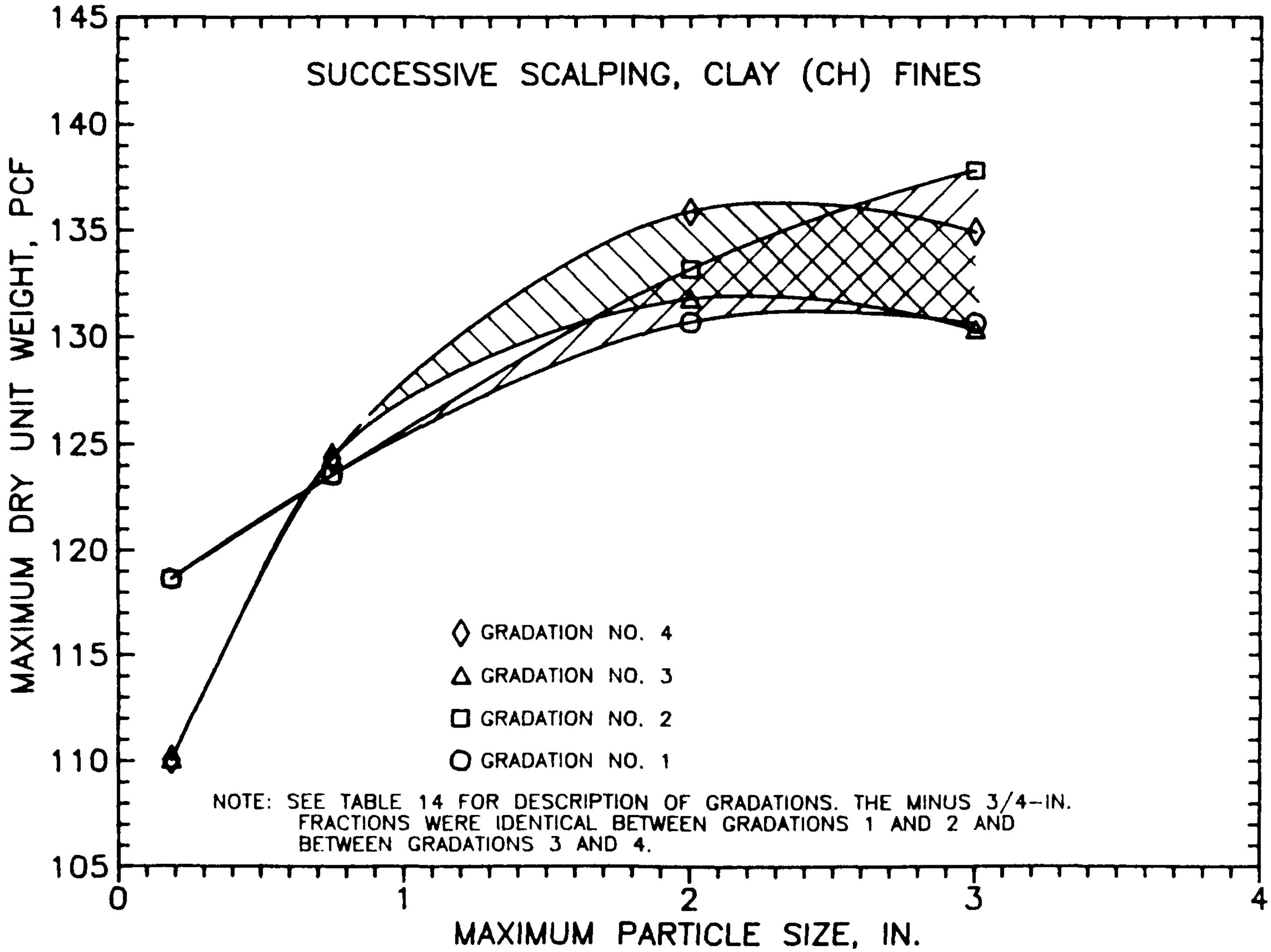


Figure 127. Maximum dry unit weight versus maximum particle size, all test gradations with clay (CH) fines

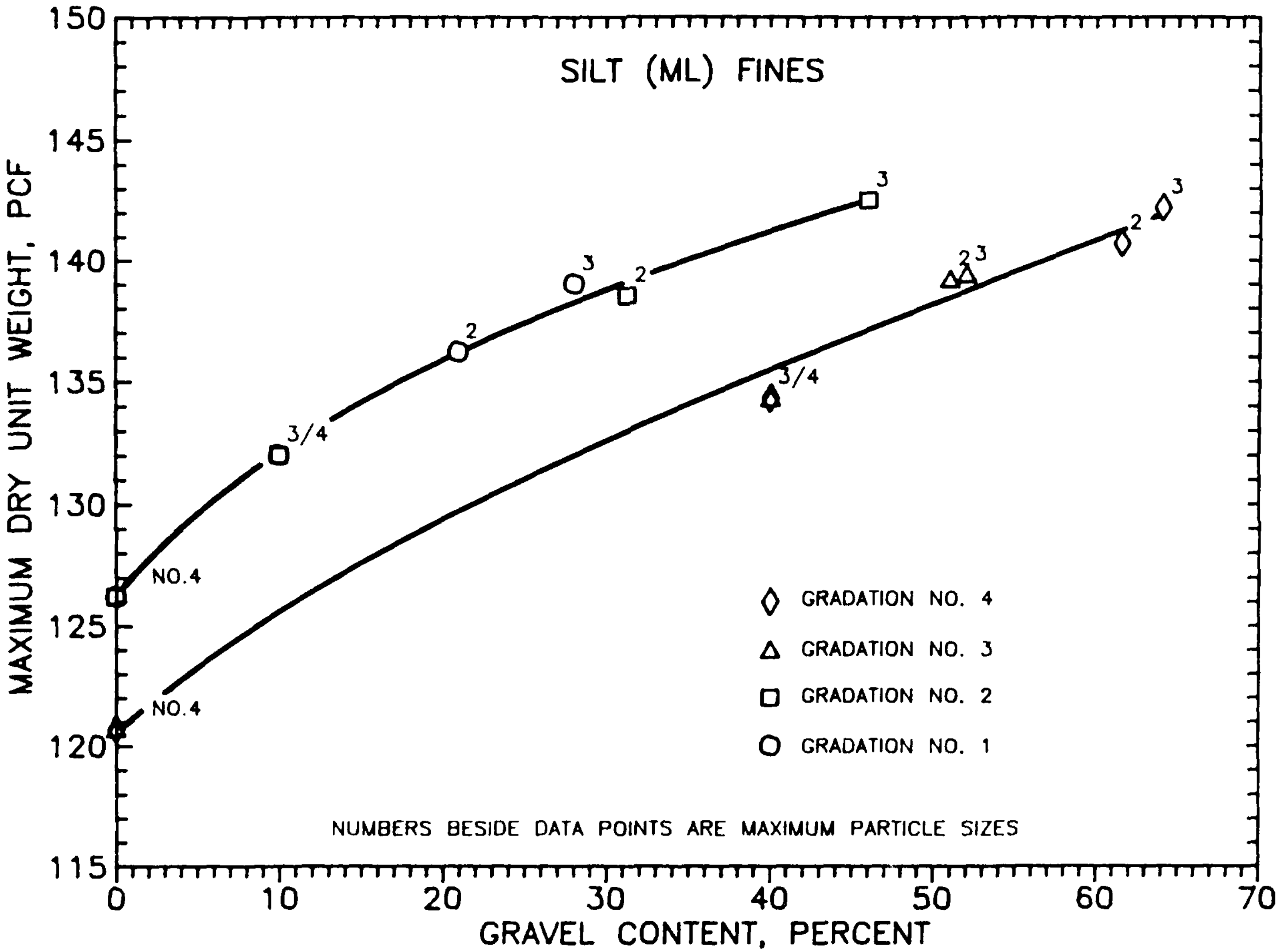


Figure 128. Maximum dry unit weight versus gravel content, all test gradations wi h silt (ML) fines

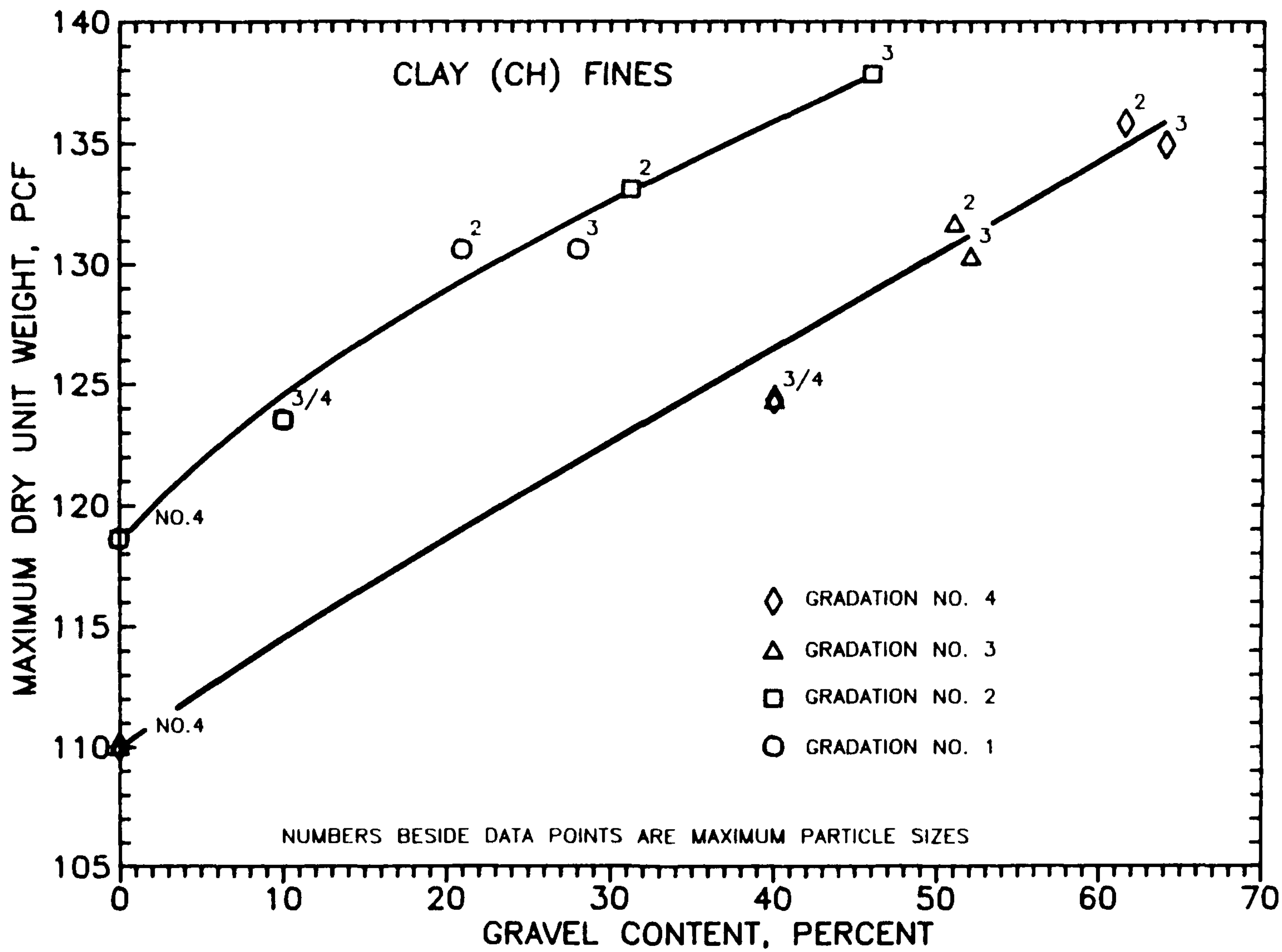


Figure 129. Maximum dry unit weight versus gravel content, all test gradations with clay (CH) fines

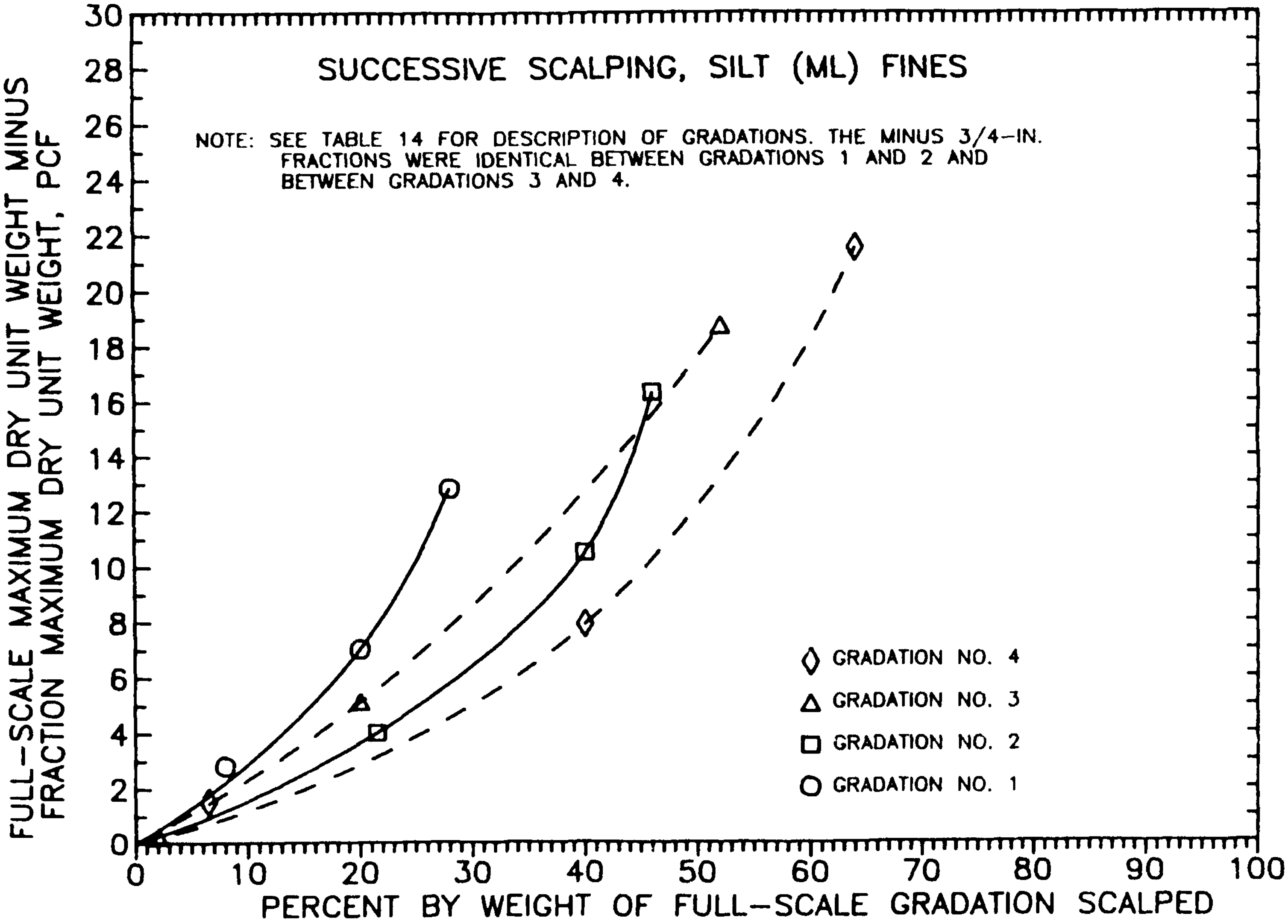


Figure 130. Deviation of fractions' maximum dry unit weights from those of minus 3-in. parent gradations versus percent scalped, silt (ML) fines

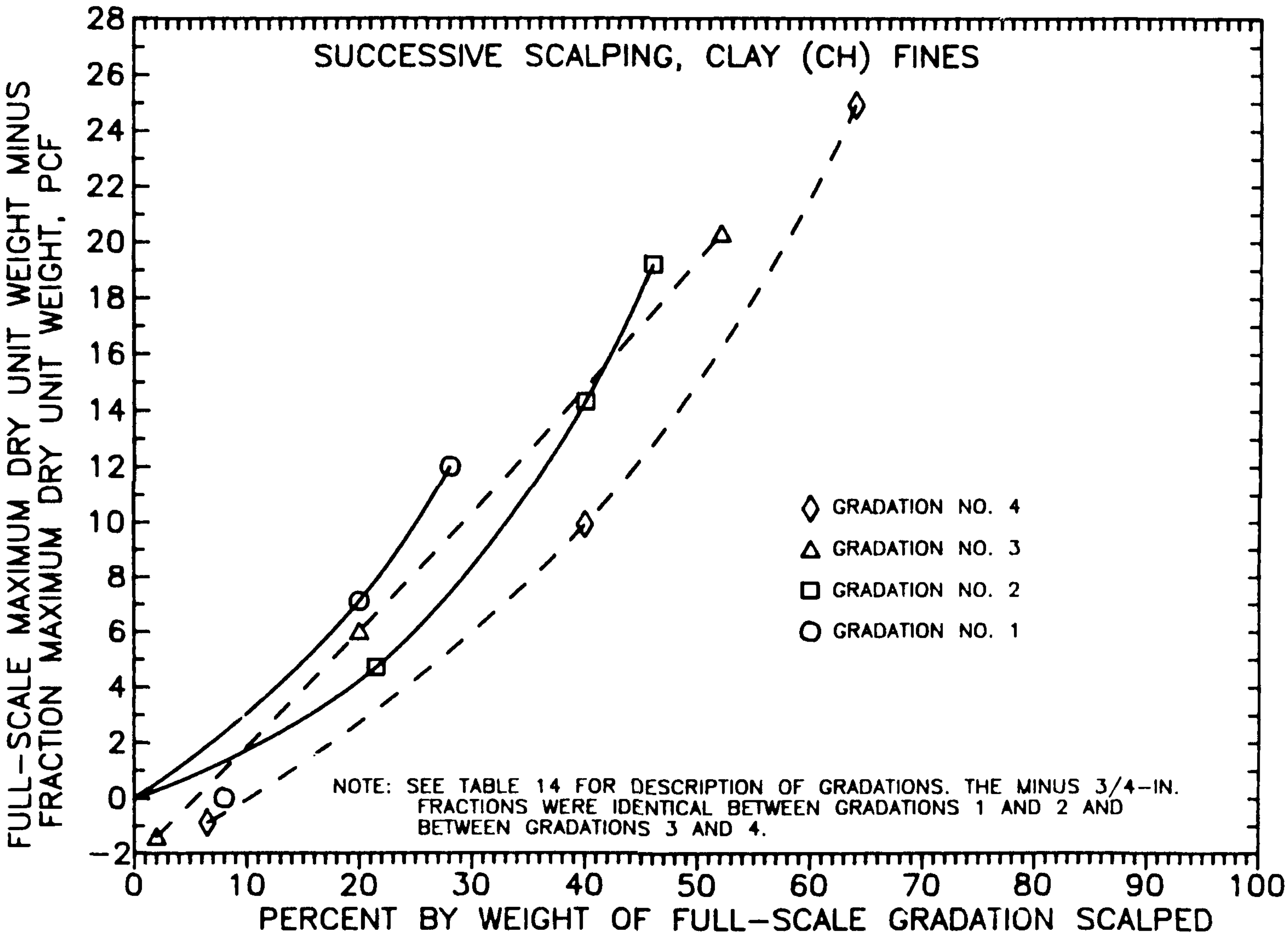


Figure 131. Deviation of fractions' maximum dry unit weights from those of minus 3-in. parent gradations versus percent scalped, clay (CH) fines

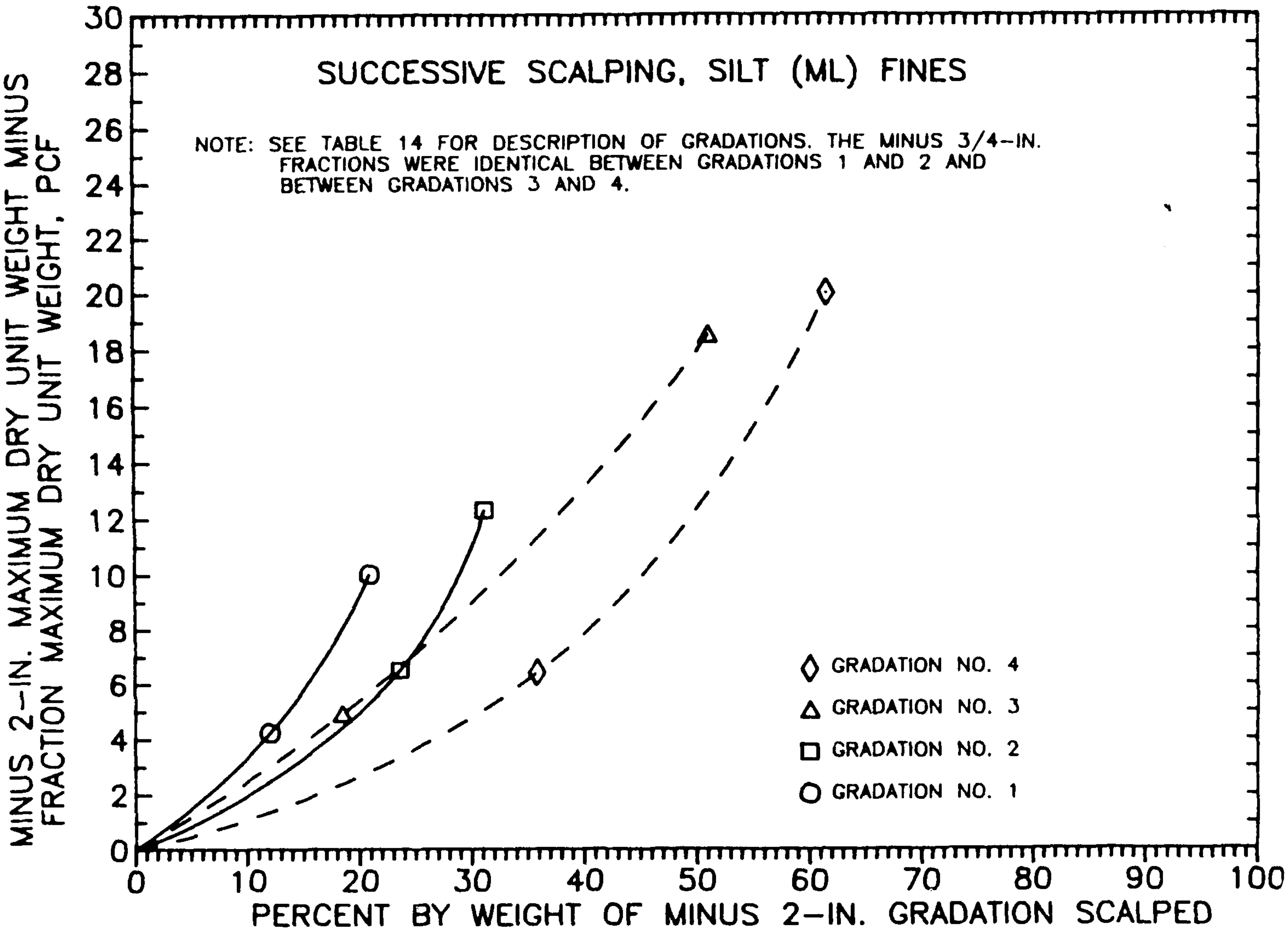


Figure 132. Deviation of fractions' maximum dry unit weights from those of minus 2-in. parent gradations versus percent scalped, silt (ML) fines

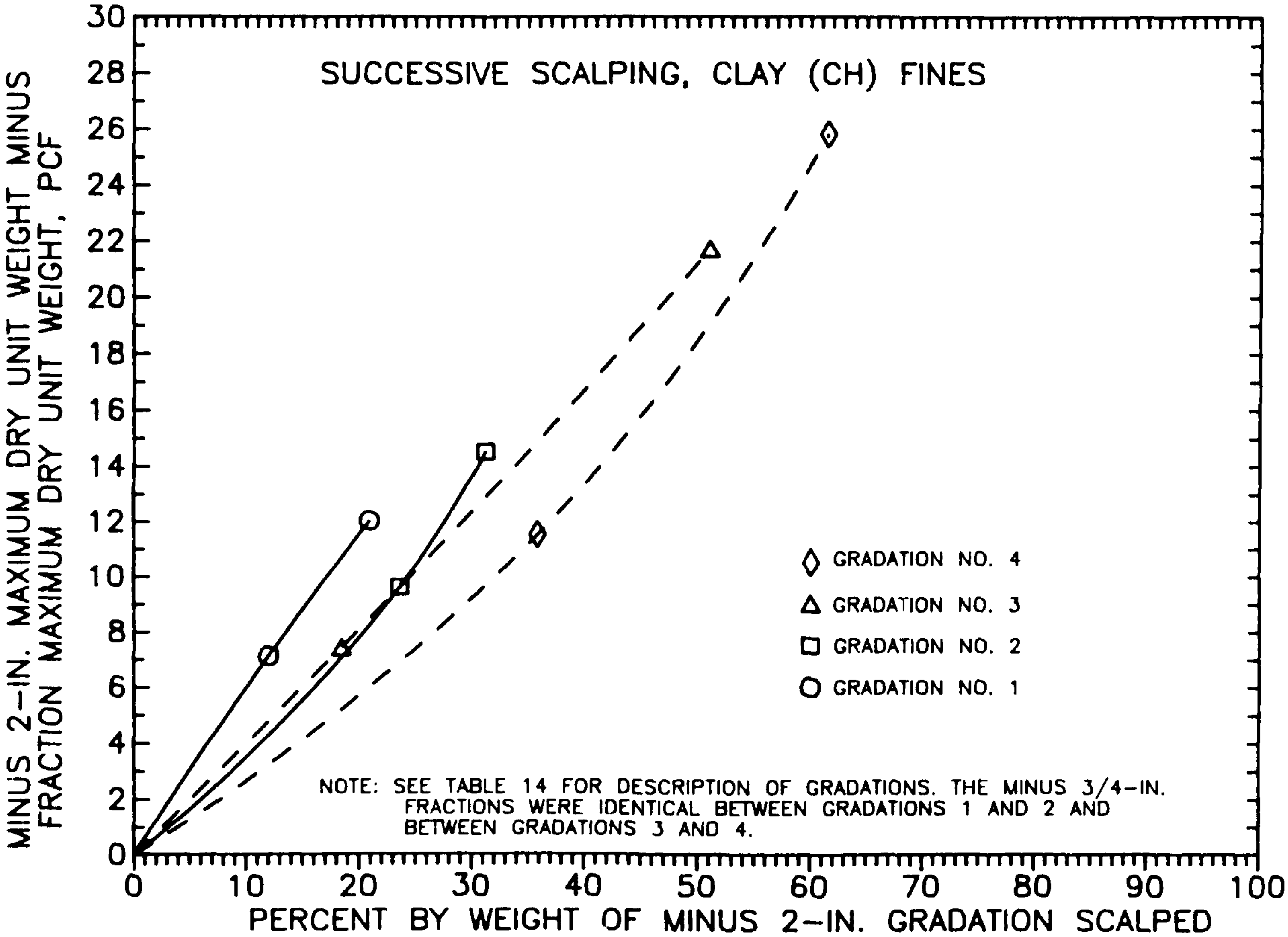


Figure 133. Deviation of fractions' maximum dry unit weights from those of minus 2-in. parent gradations versus percent scalped, clay (CH) fines

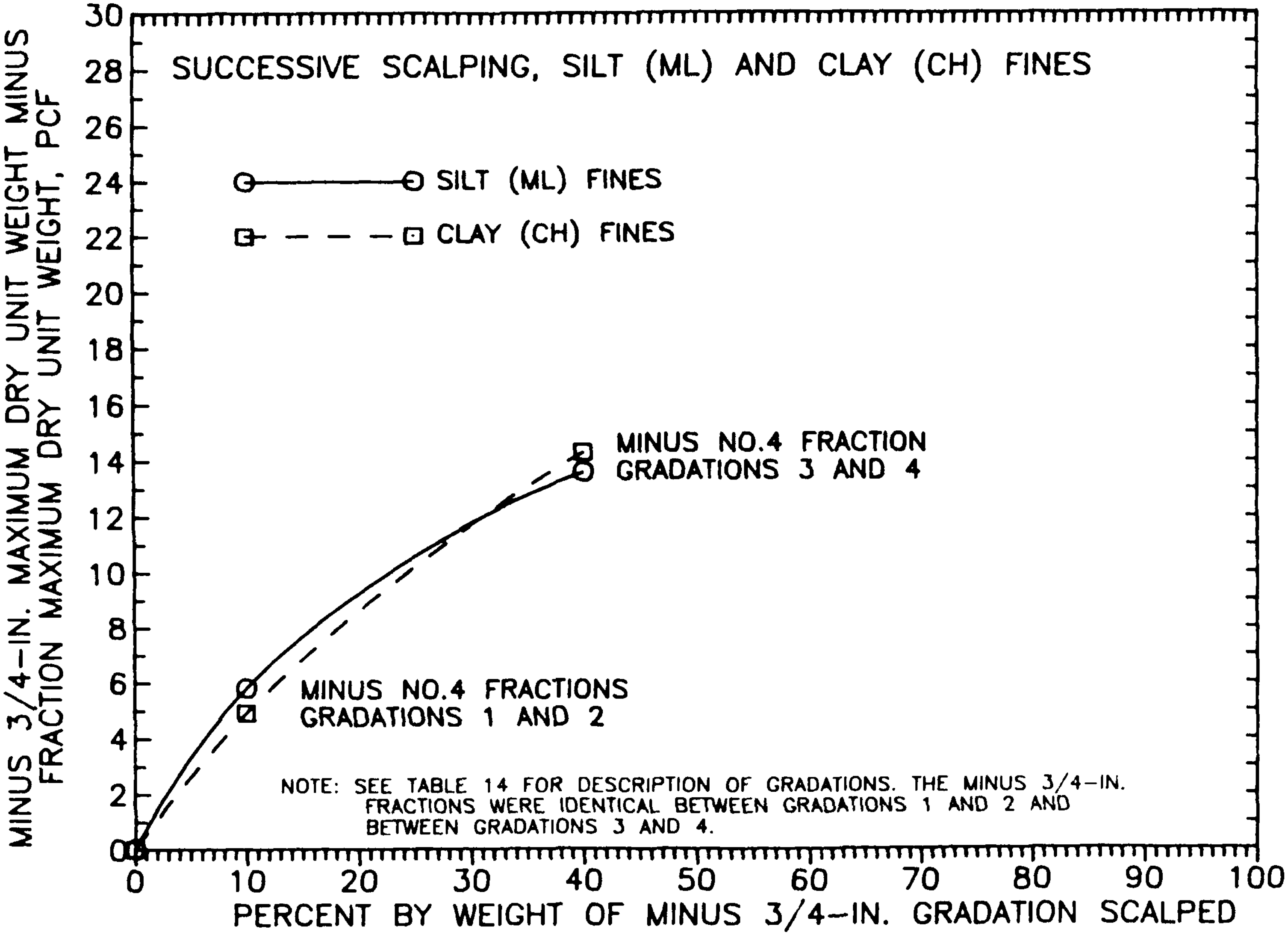


Figure 134. Deviation of fractions' maximum dry unit weights from those of minus 3/4-in. parent gradations versus percent scalped, silt (ML) and clay (CH) fines

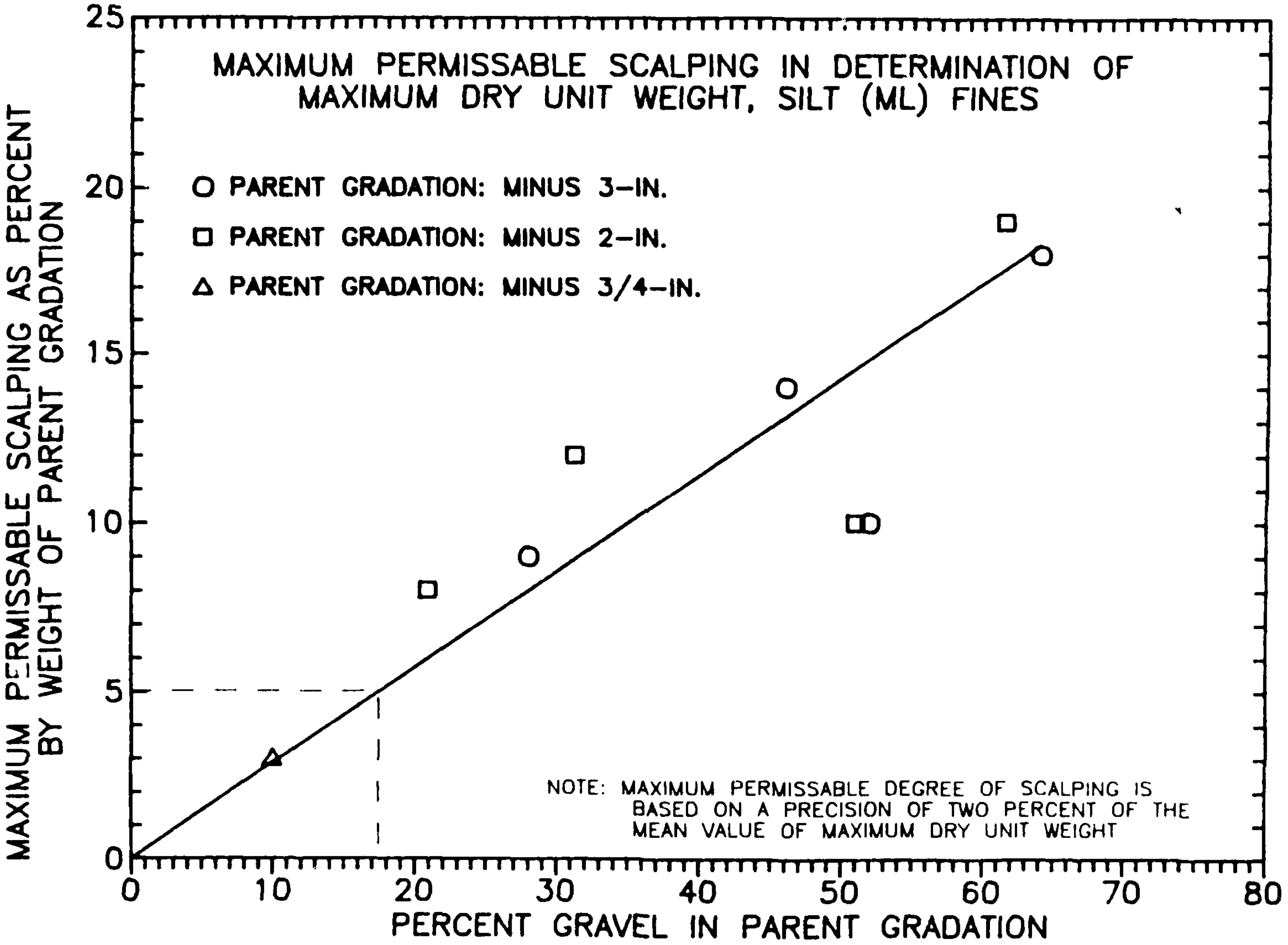


Figure 135. Maximum permissible degree of scalping versus gravel content of the parent gradation based on a precision of two percent of the mean value of maximum dry unit weight, silt (ML) fines

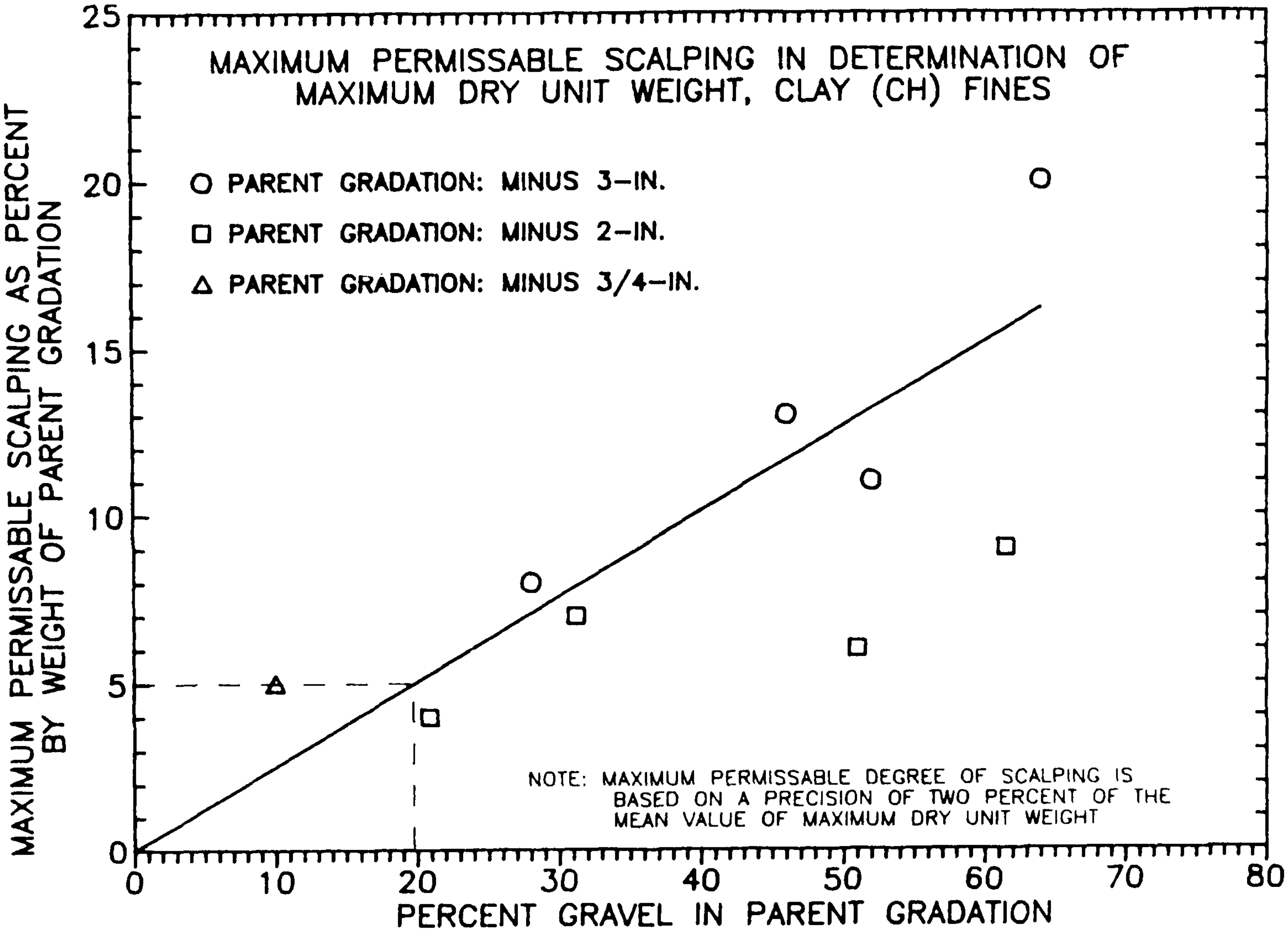


Figure 136. Maximum permissible degree of scalping versus gravel content of the parent gradation based on a precision of two percent of the mean value of maximum dry unit weight, clay (CH) fines

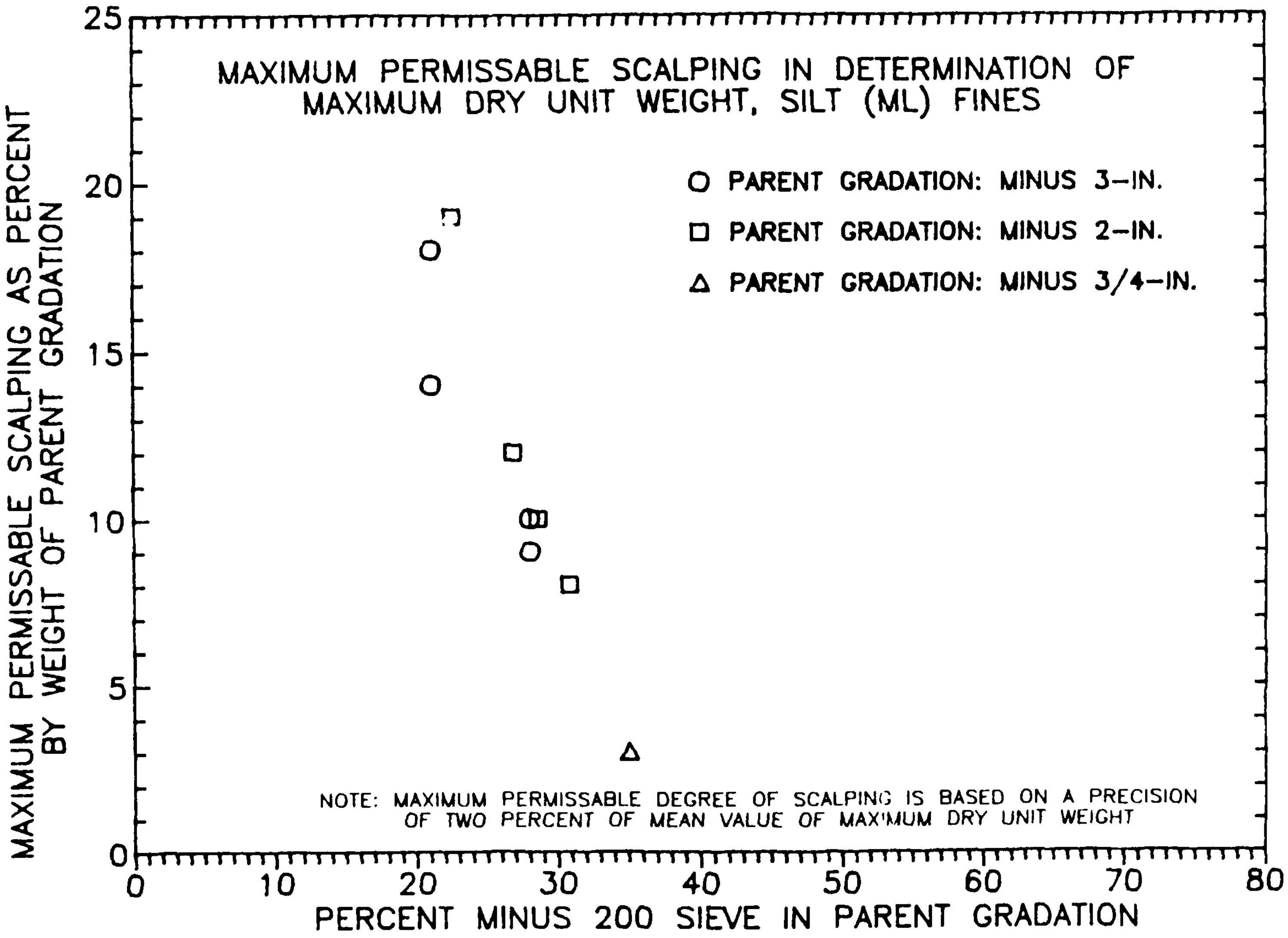


Figure 137. Maximum permissible degree of scalping in determination of maximum dry unit weight versus percent fines, silt (ML) fines

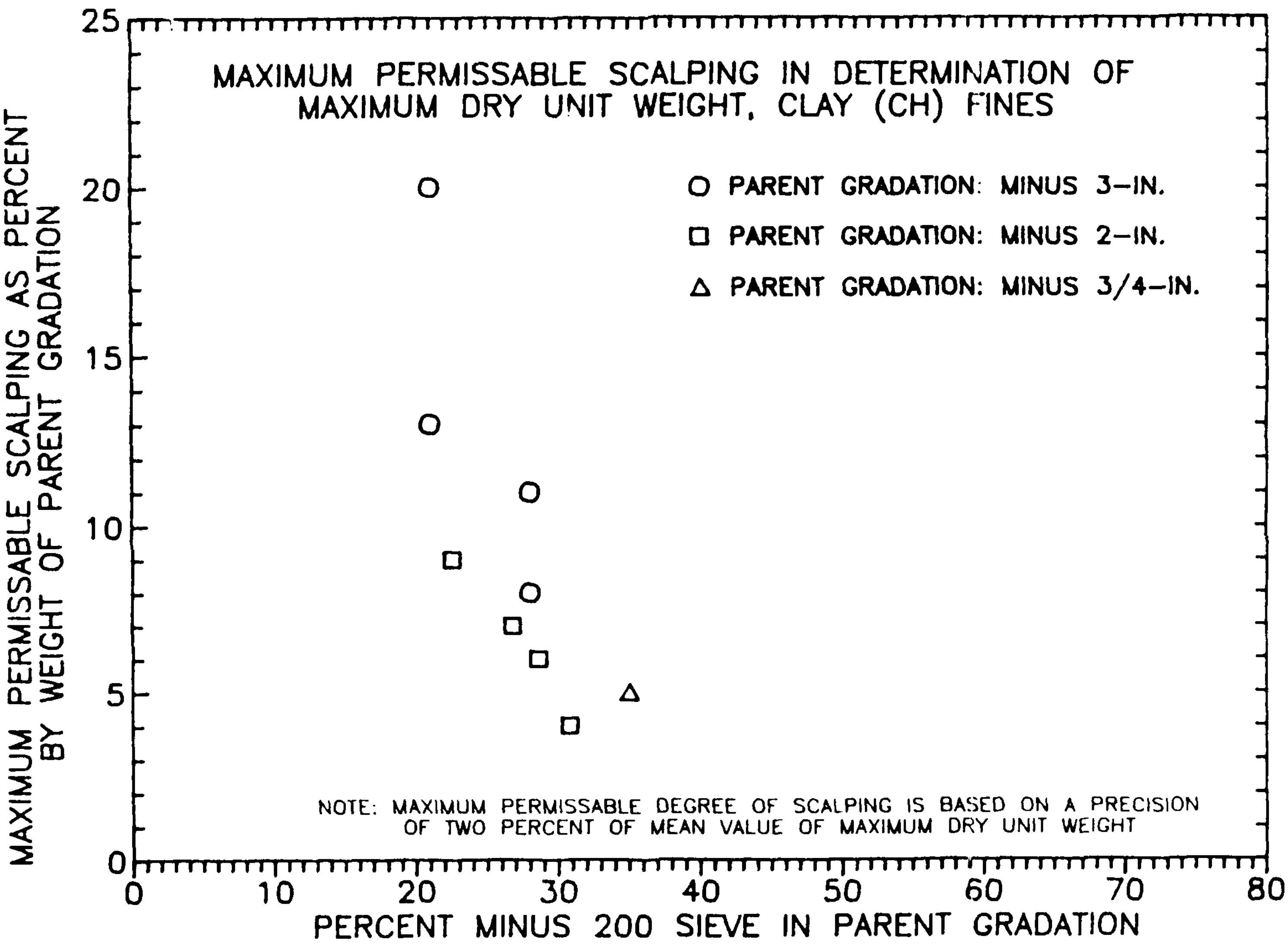


Figure 138. Maximum permissible degree of scalping in determination of maximum dry unit weight versus percent fines, clay (CH) fines

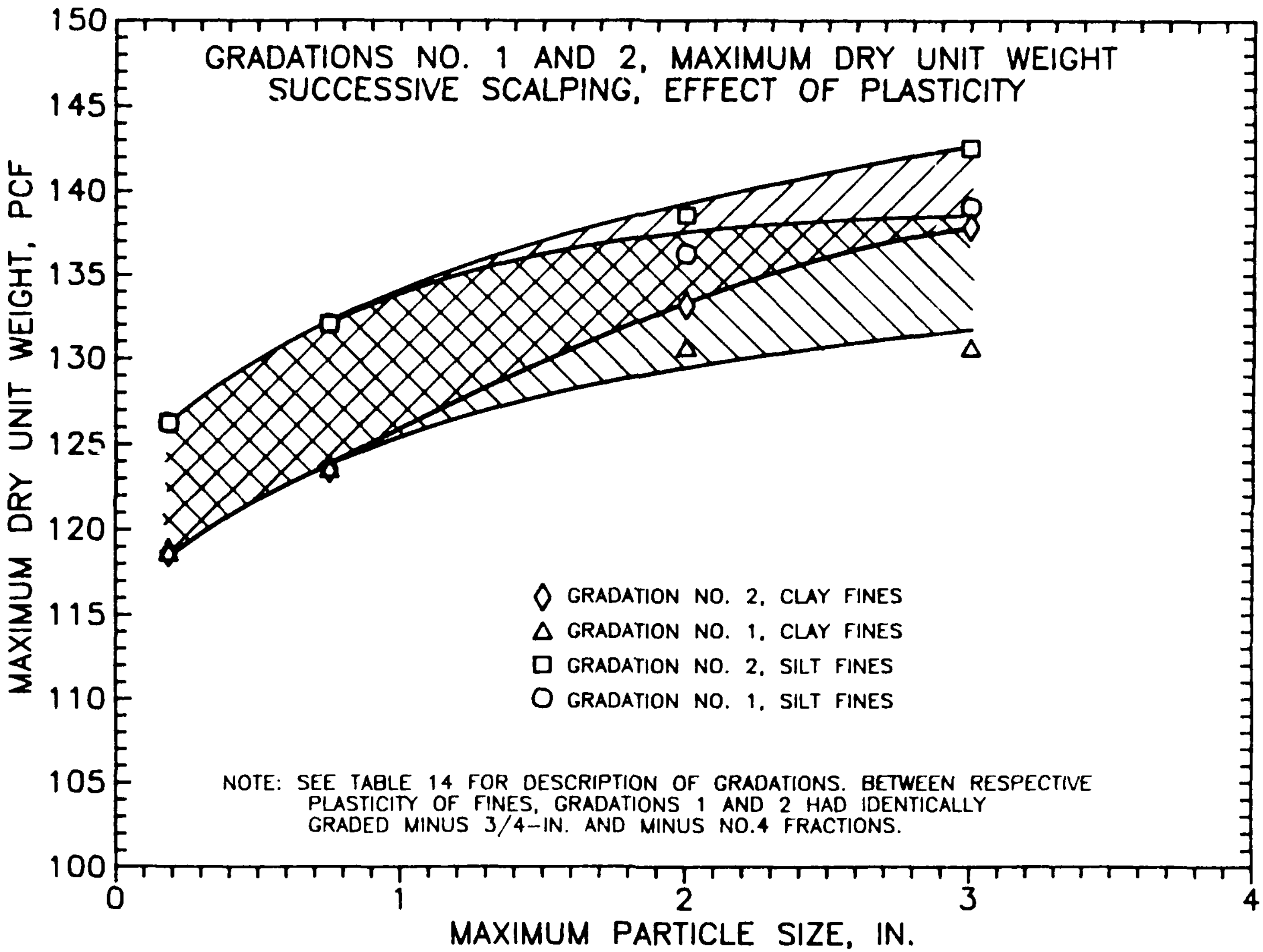


Figure 139. Maximum dry unit weight versus maximum particle size, effects of plasticity of fines, gradations Nos. 1 and 2

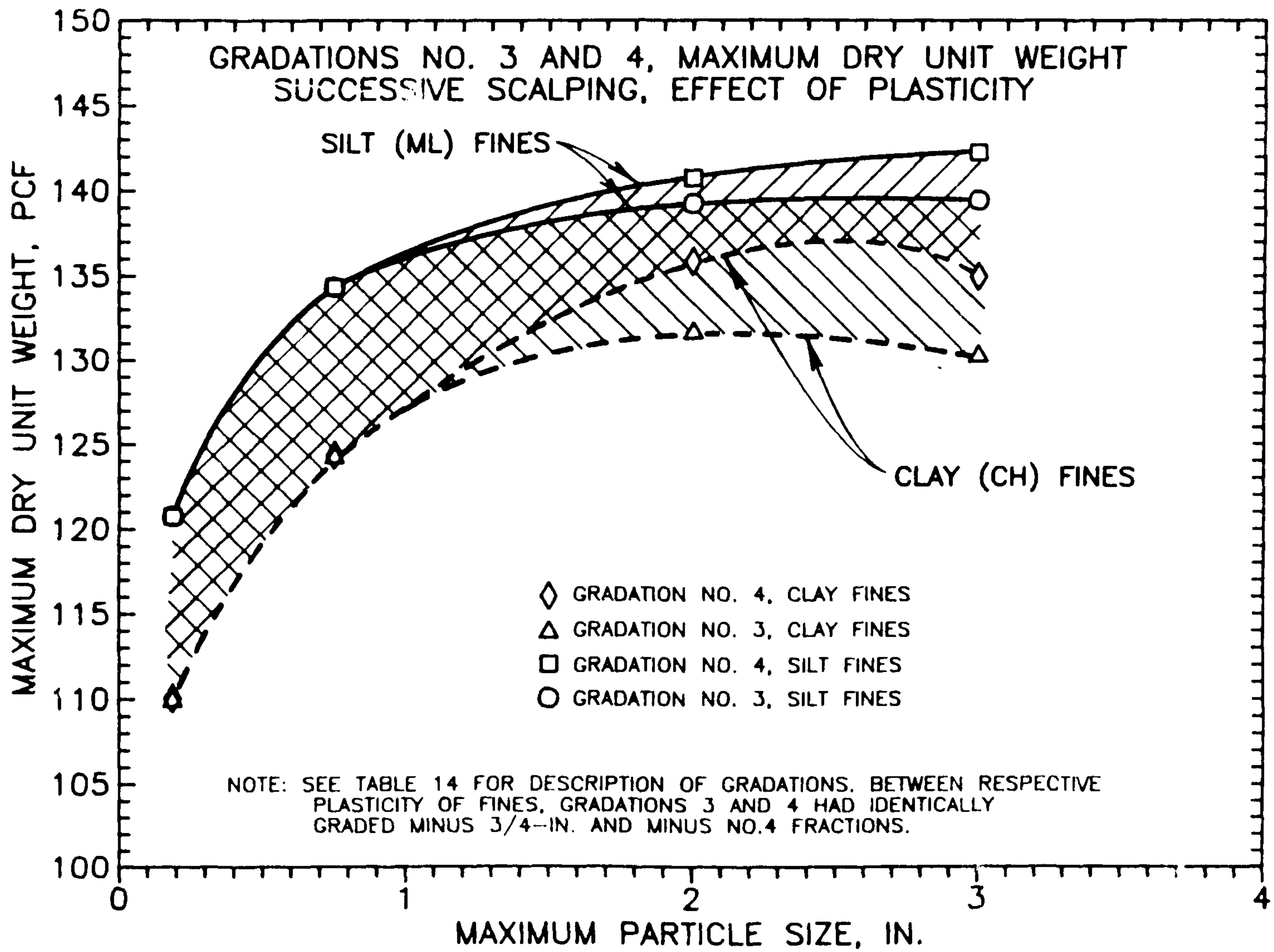


Figure 140. Maximum dry unit weight versus maximum particle size, effects of plasticity of fines, gradations Nos. 3 and 4

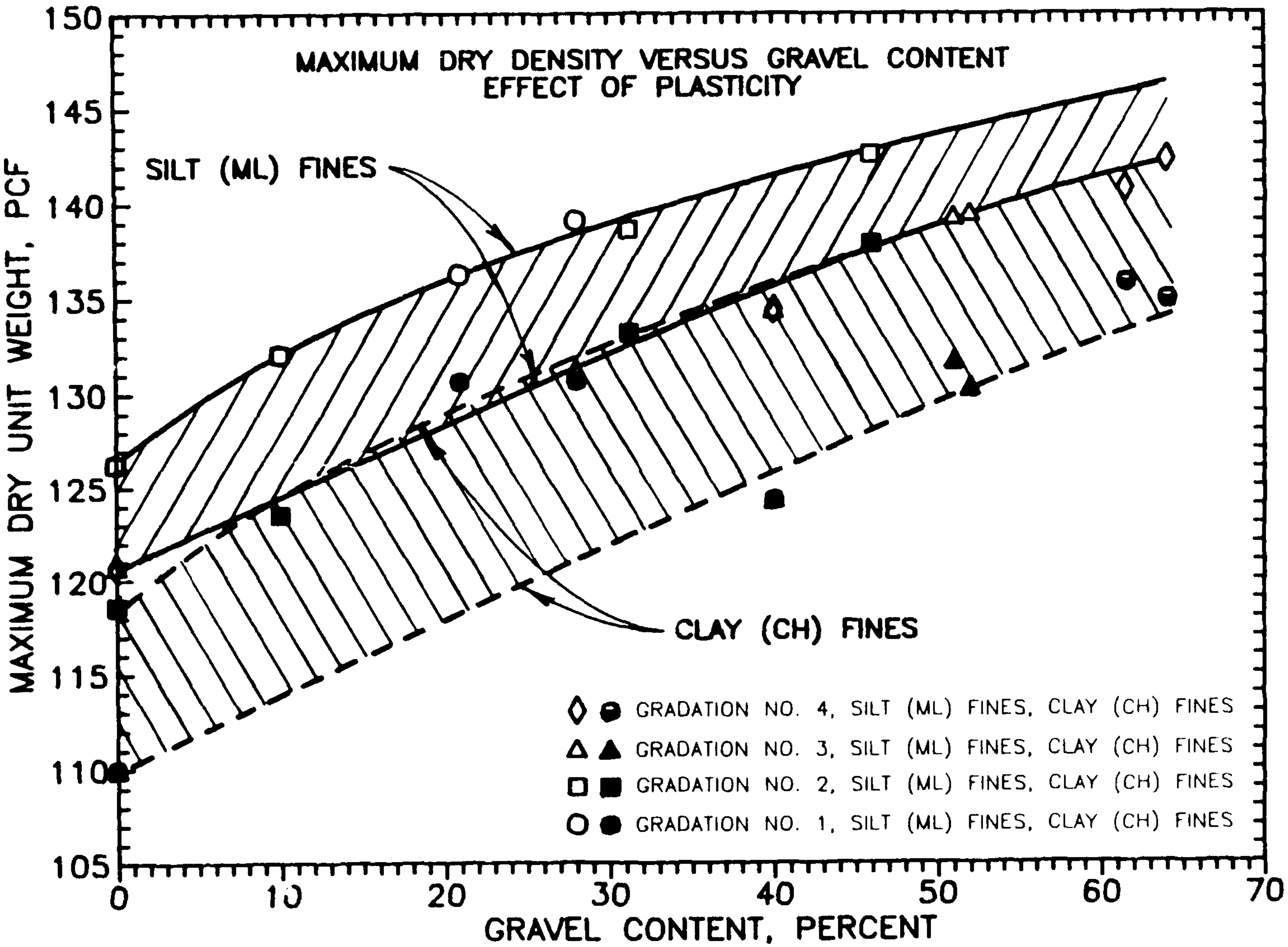


Figure 141. Maximum dry unit weight versus gravel content, effects of plasticity of fines, all test gradations

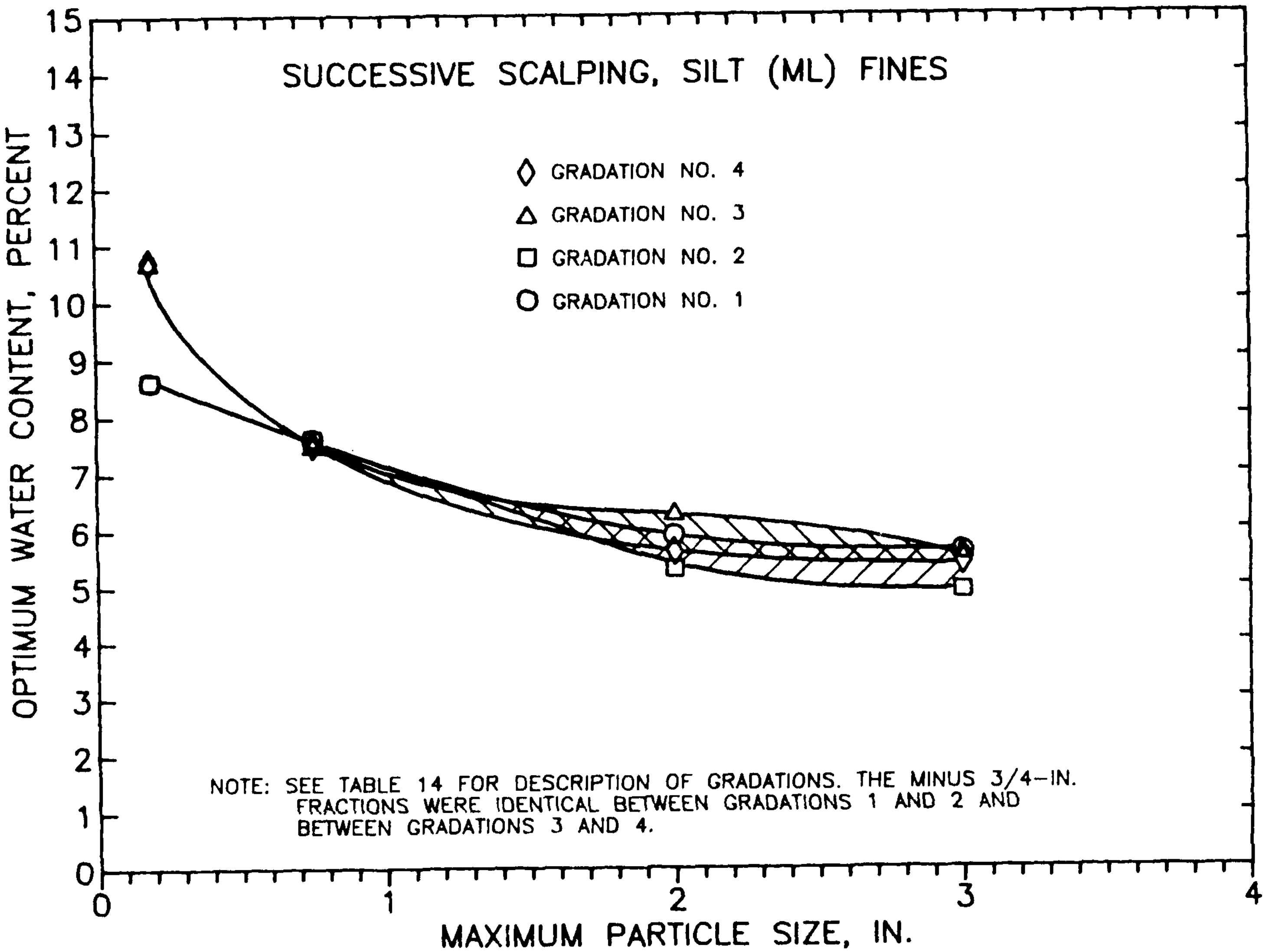


Figure 142. Optimum water content versus maximum particle size, all test gradations with silt (ML) fines

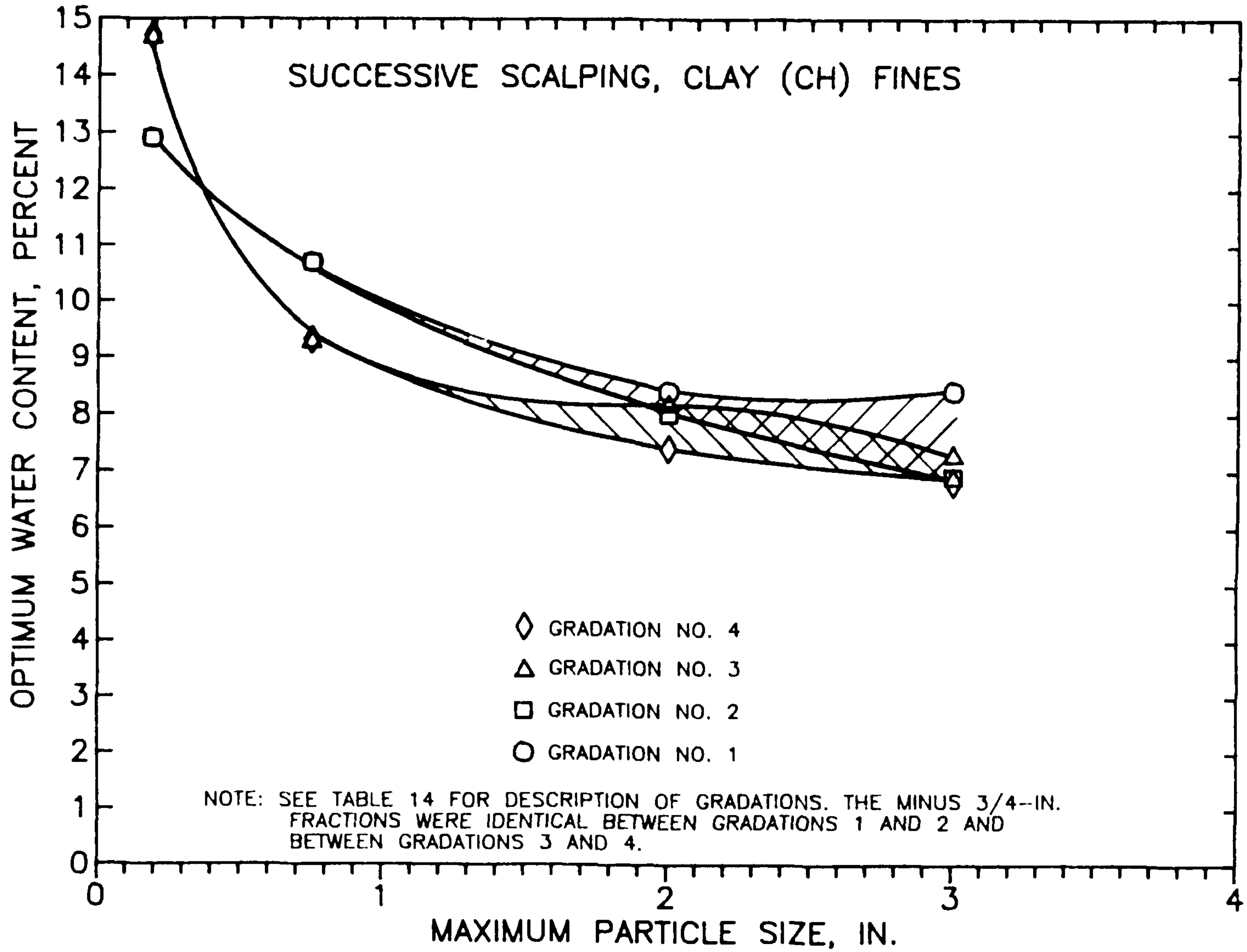


Figure 143. Optimum water content versus maximum particle size, all test gradations with clay (CH) fines

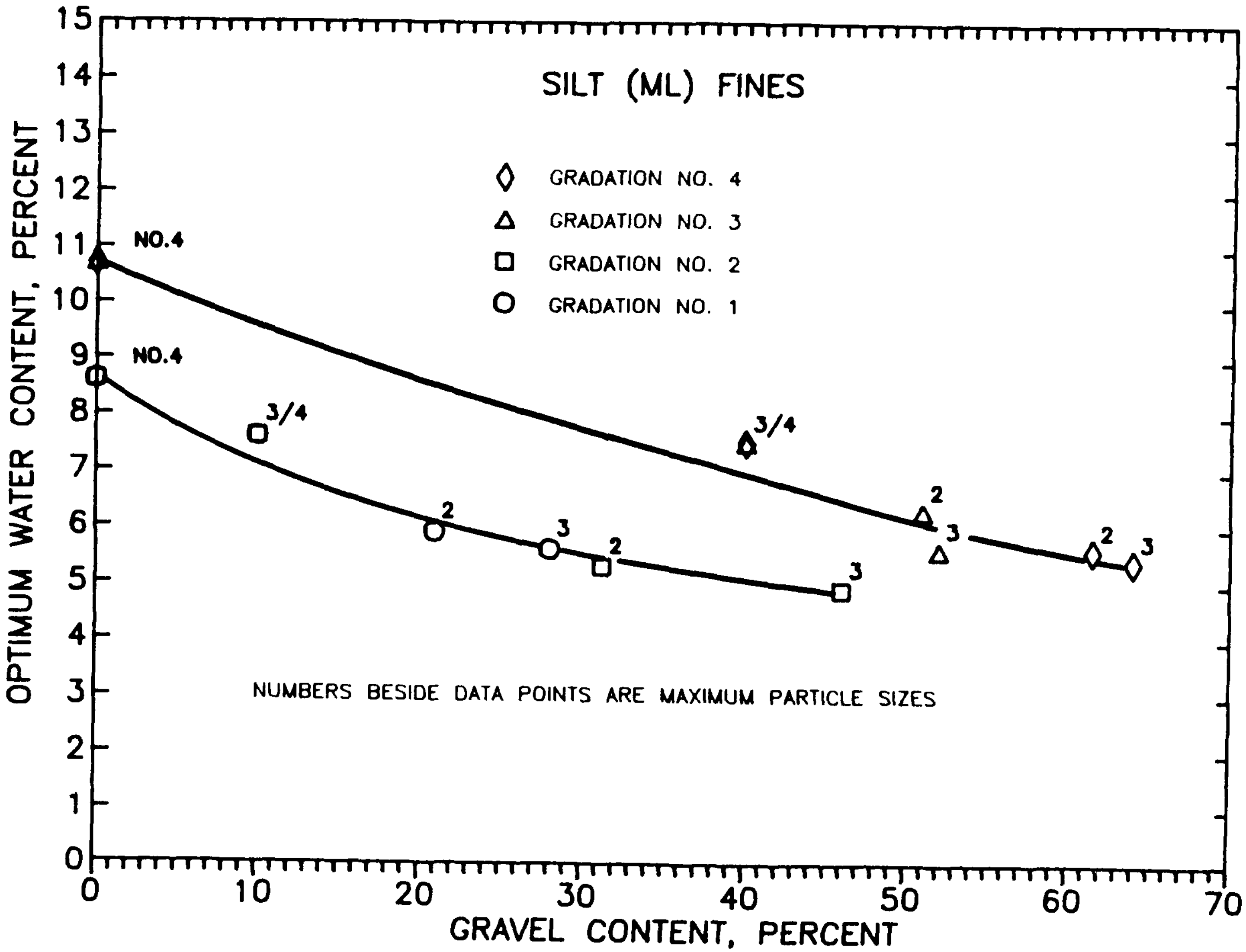


Figure 144. Optimum water content versus gravel content, all test gradations with silt (ML) fines

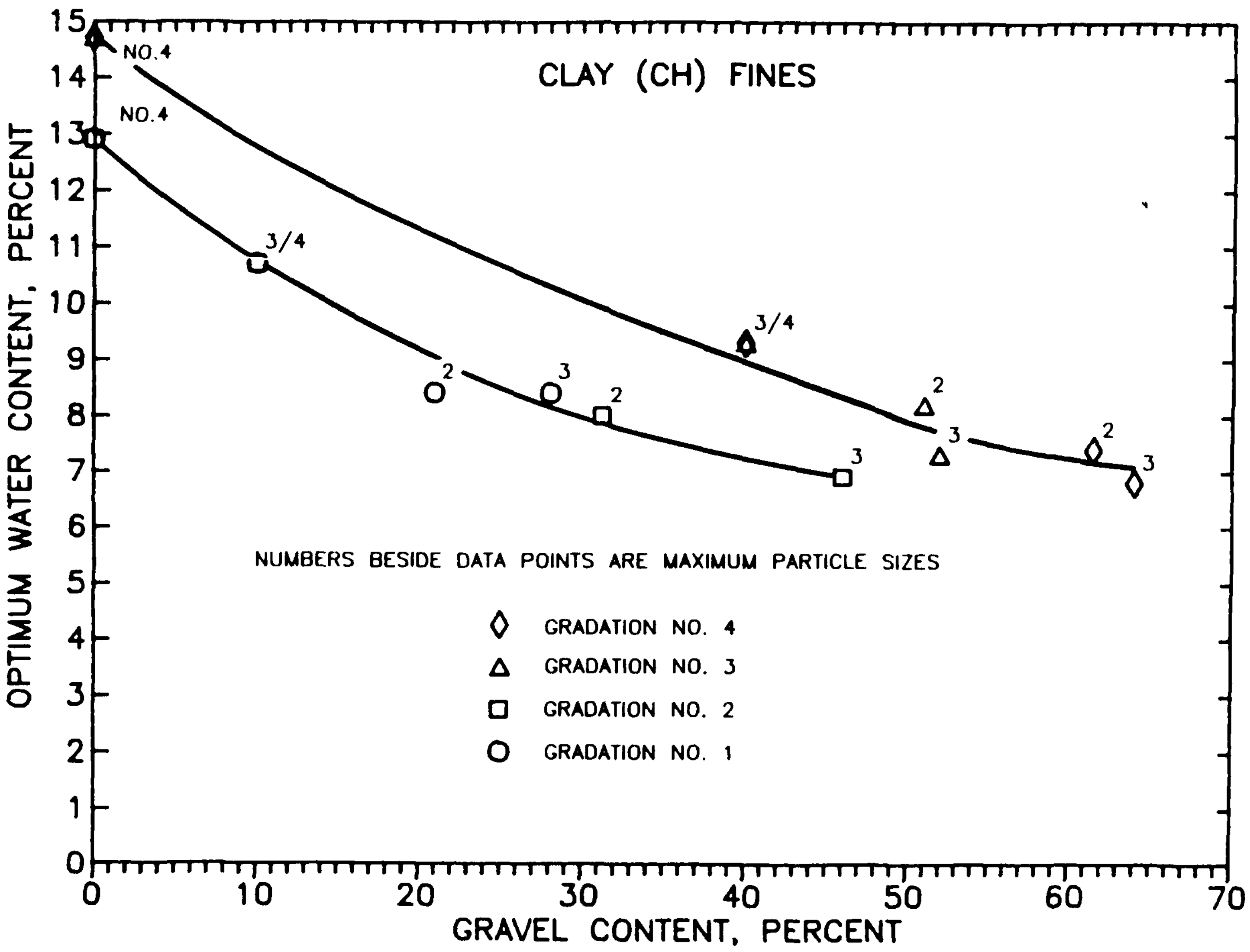


Figure 145. Optimum water content versus gravel content, all test gradations with clay (CH) fines

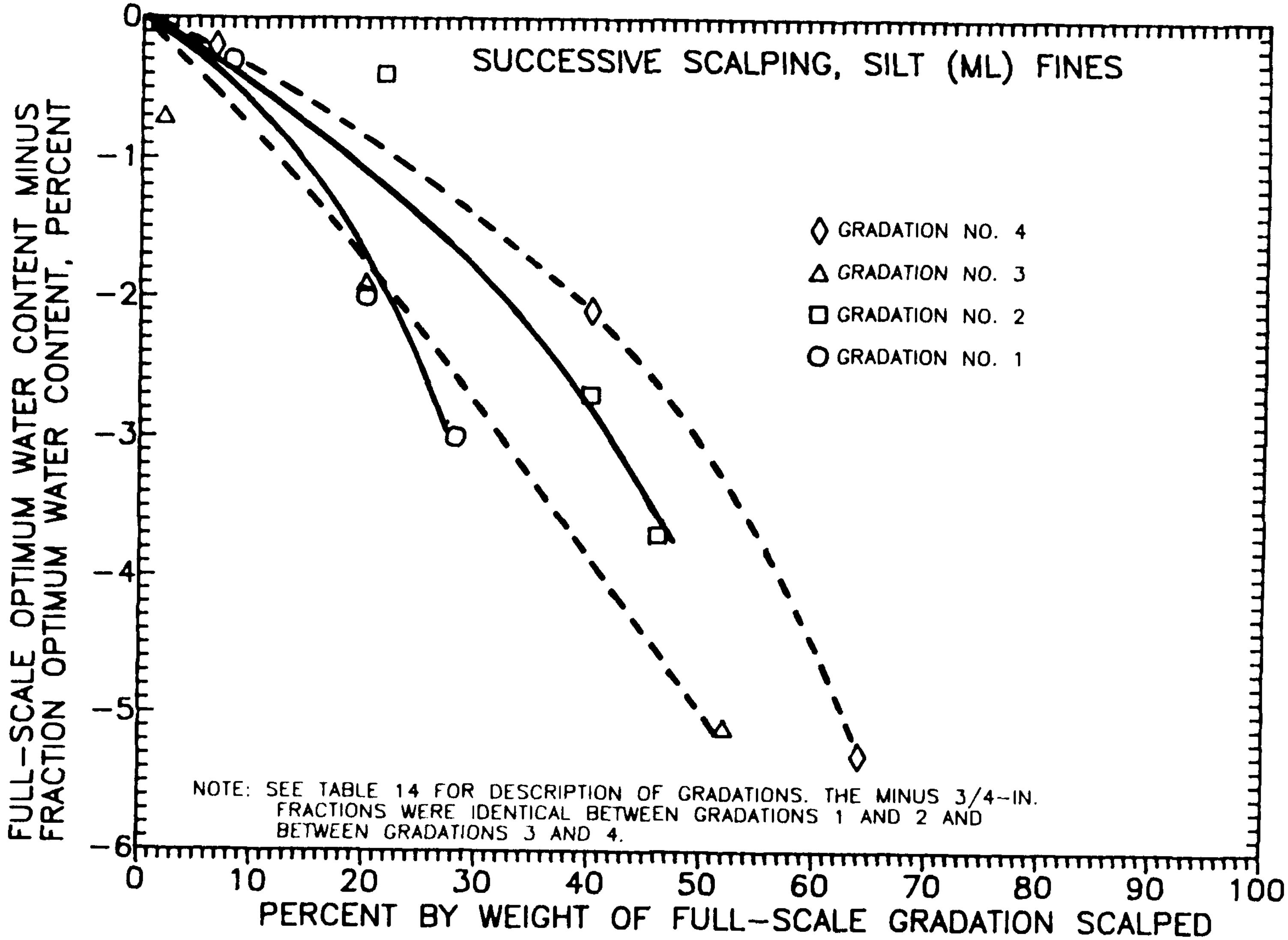


Figure 146. Deviation of fractions' optimum water contents from those of minus 3-in. parent gradations versus percent scalped, silt (ML) fines

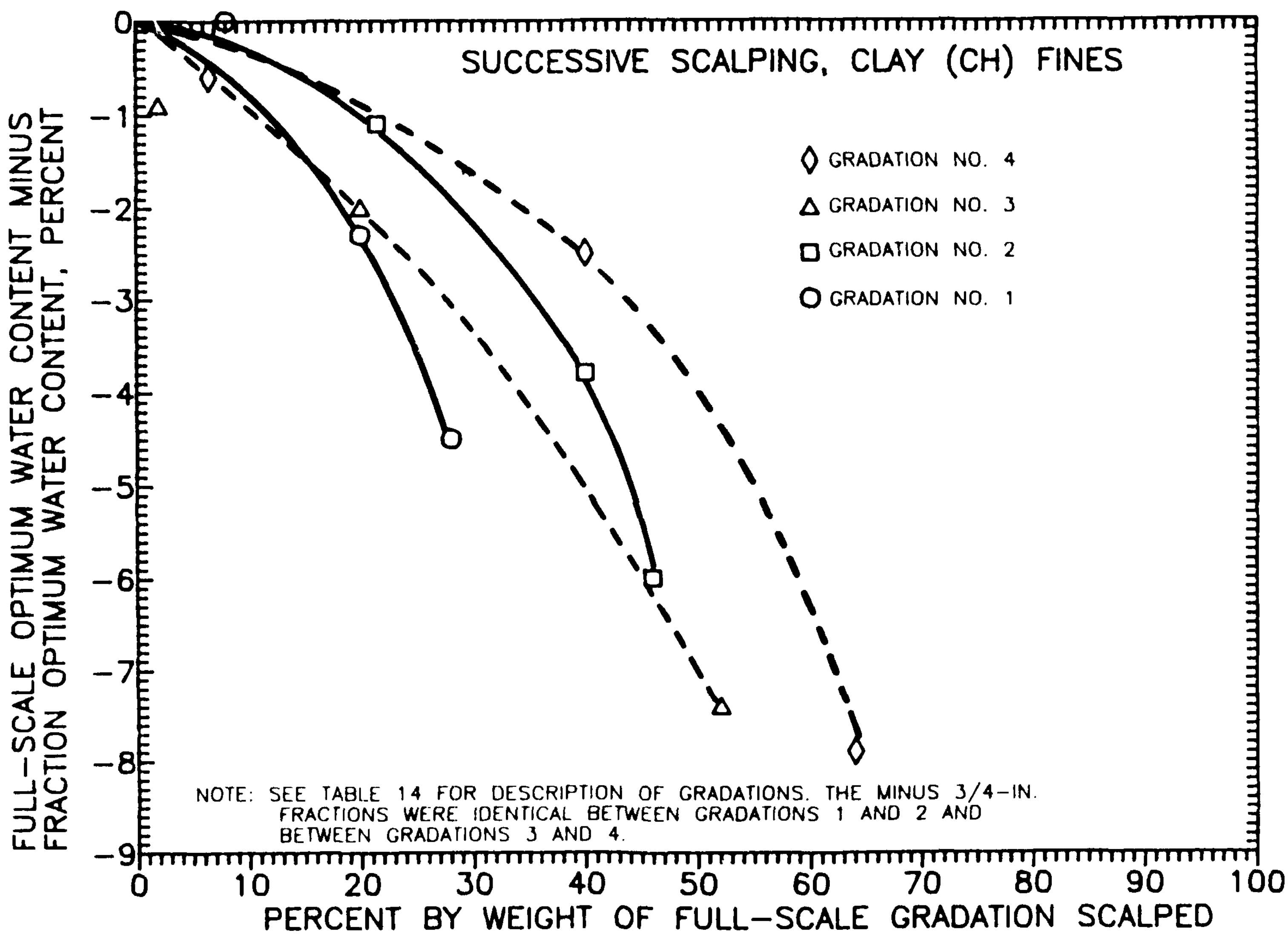


Figure 147. Deviation of fractions' optimum water contents from those of minus 3-in. parent gradations versus percent scalped, clay (CH) fines

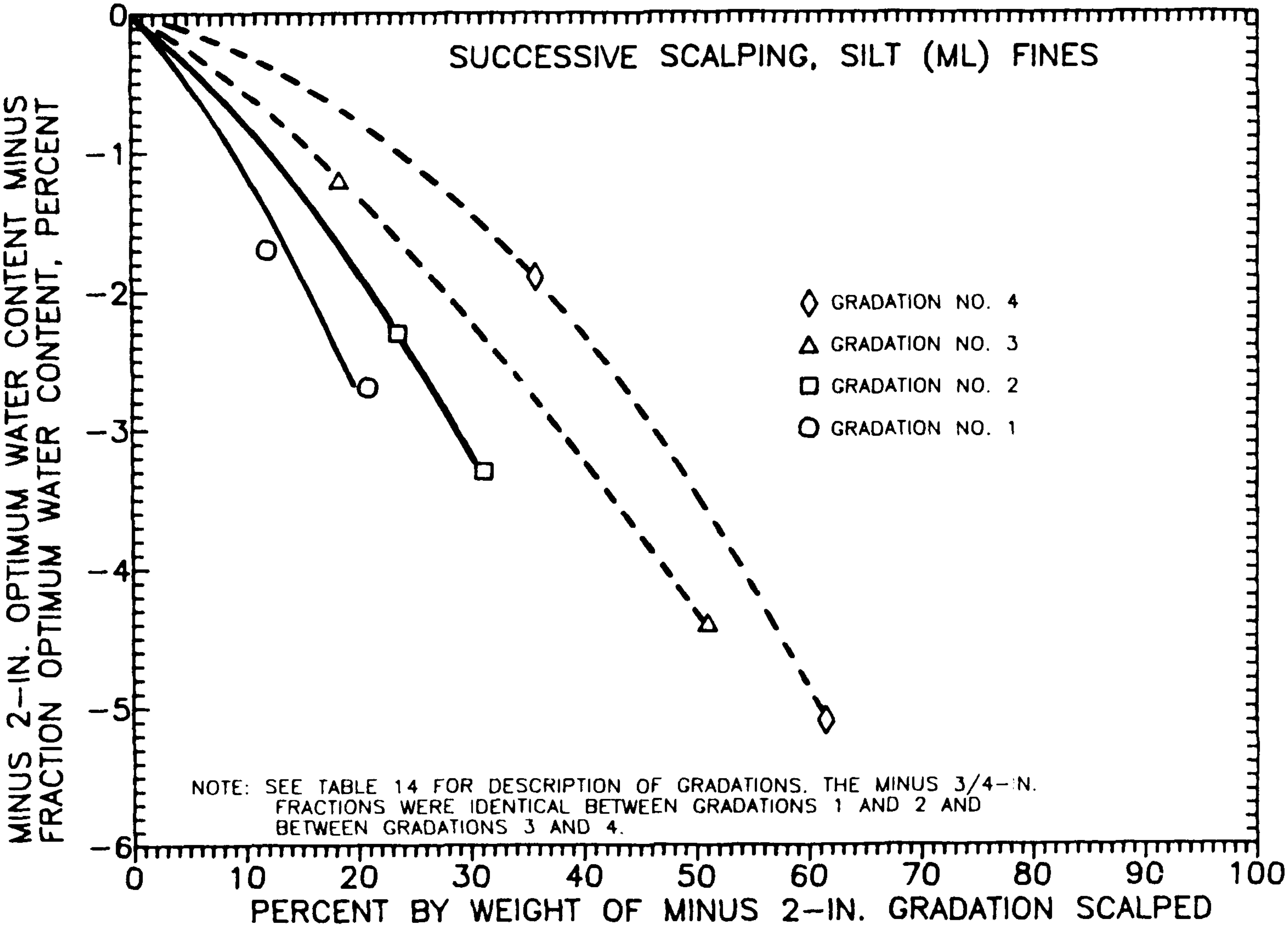


Figure 148. Deviation of fractions' optimum water contents from those of minus 2-in. parent gradations versus percent scalped, silt (ML) fines

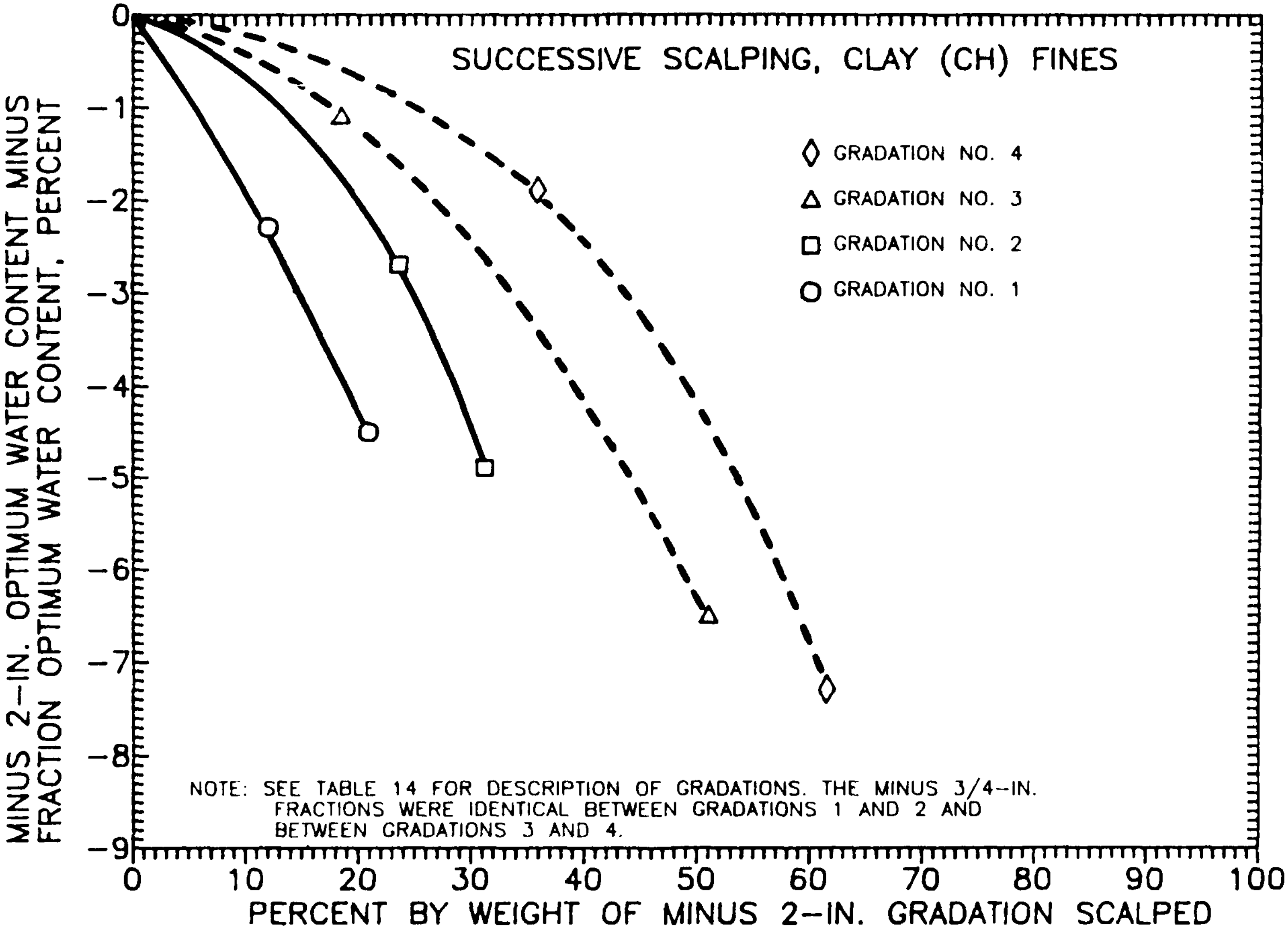


Figure 149. Deviation of fractions' optimum water contents from those of minus 2-in. parent gradations versus percent scalped, clay (CH) fines

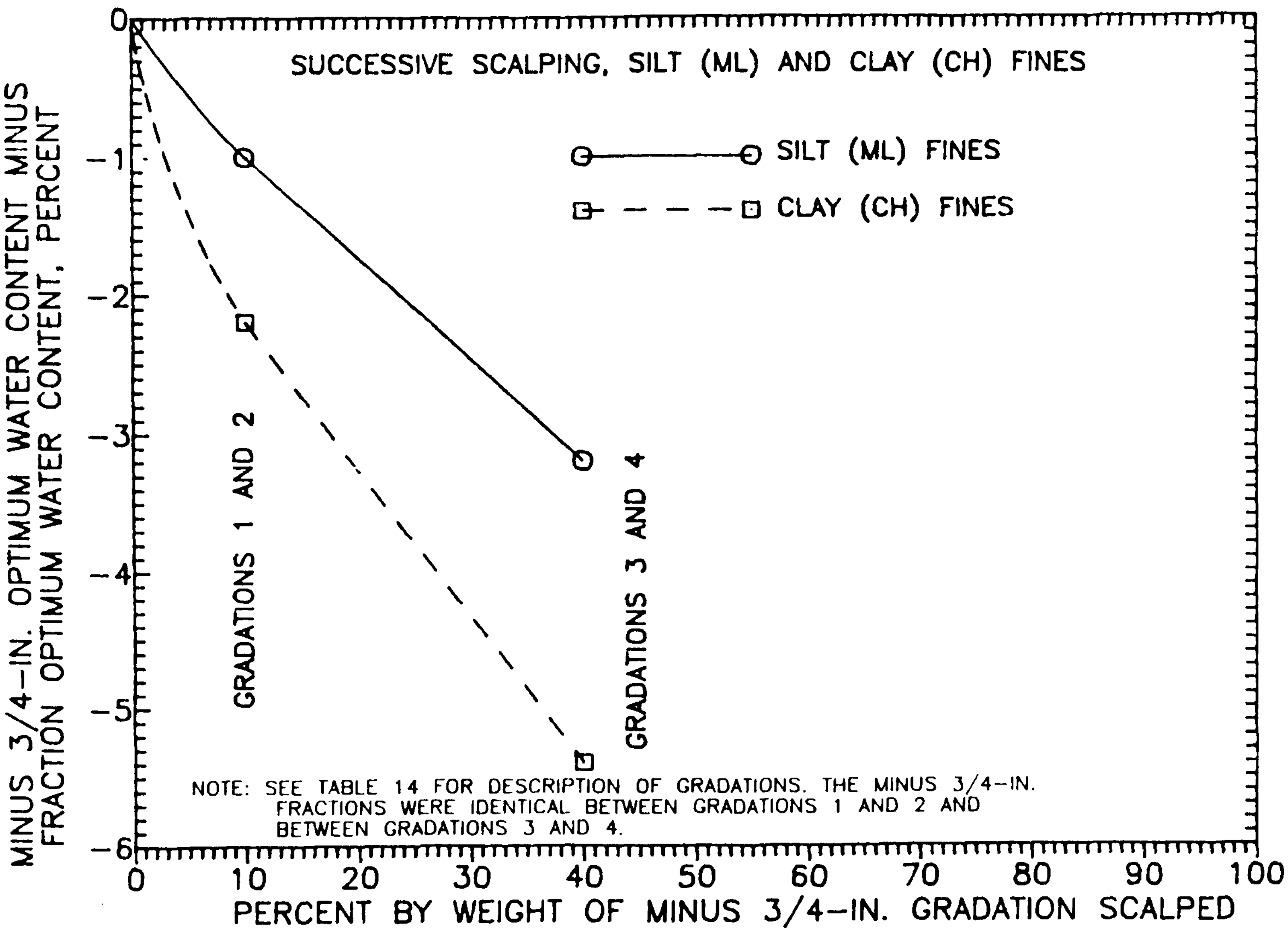


Figure 150. Deviation of fractions' optimum water contents from those of minus 3/4-in. parent gradations versus percent scalped, silt (ML) and clay (CH) fines

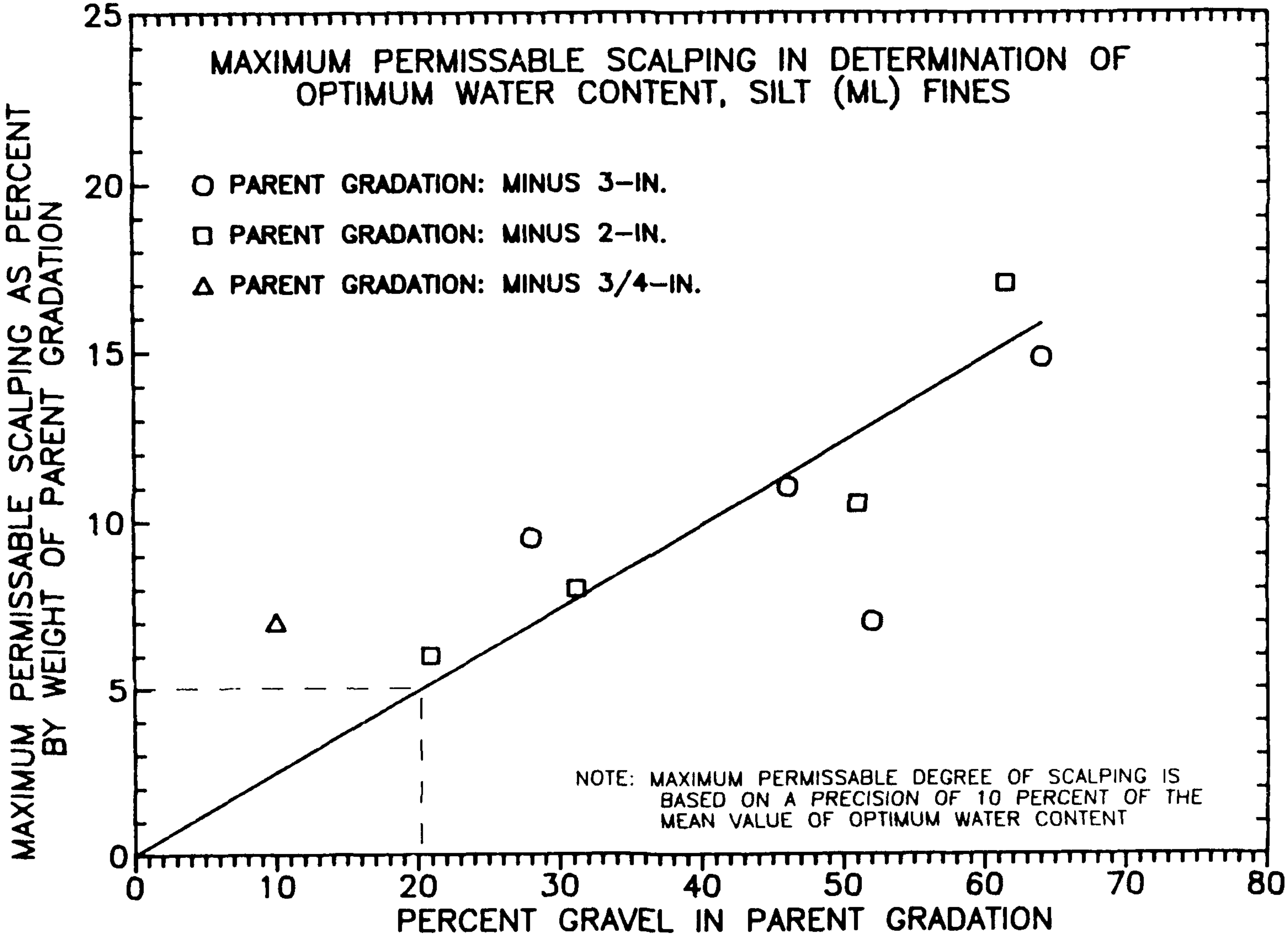


Figure 151. Maximum permissible degree of scalping versus gravel content of the parent material based on a precision of ten percent of the mean value of optimum water content, silt (ML) fines

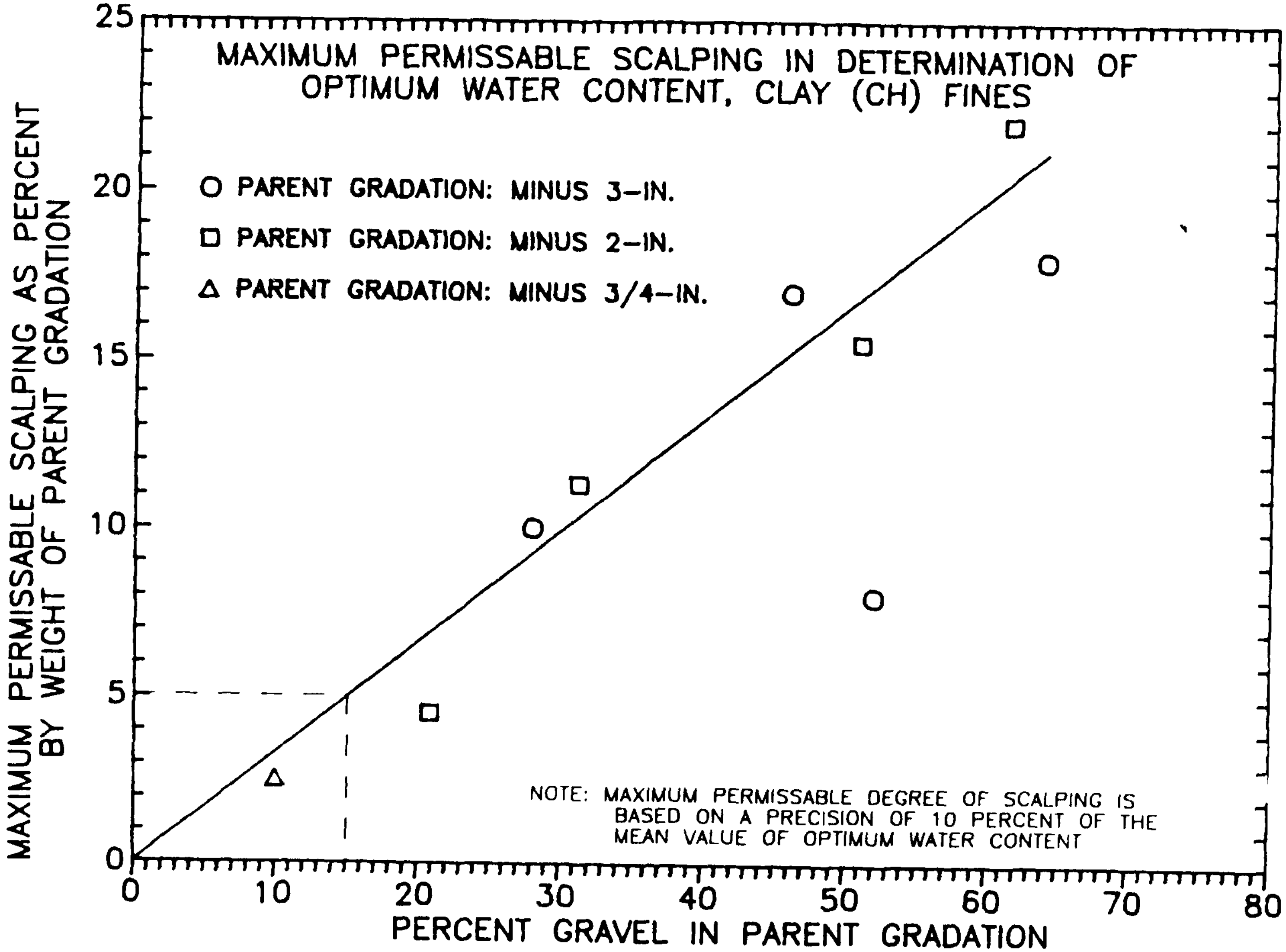


Figure 152. Maximum permissible degree of scalping versus gravel content of the parent material based on a precision of ten percent of the mean value of optimum water content, clay (CH) fines

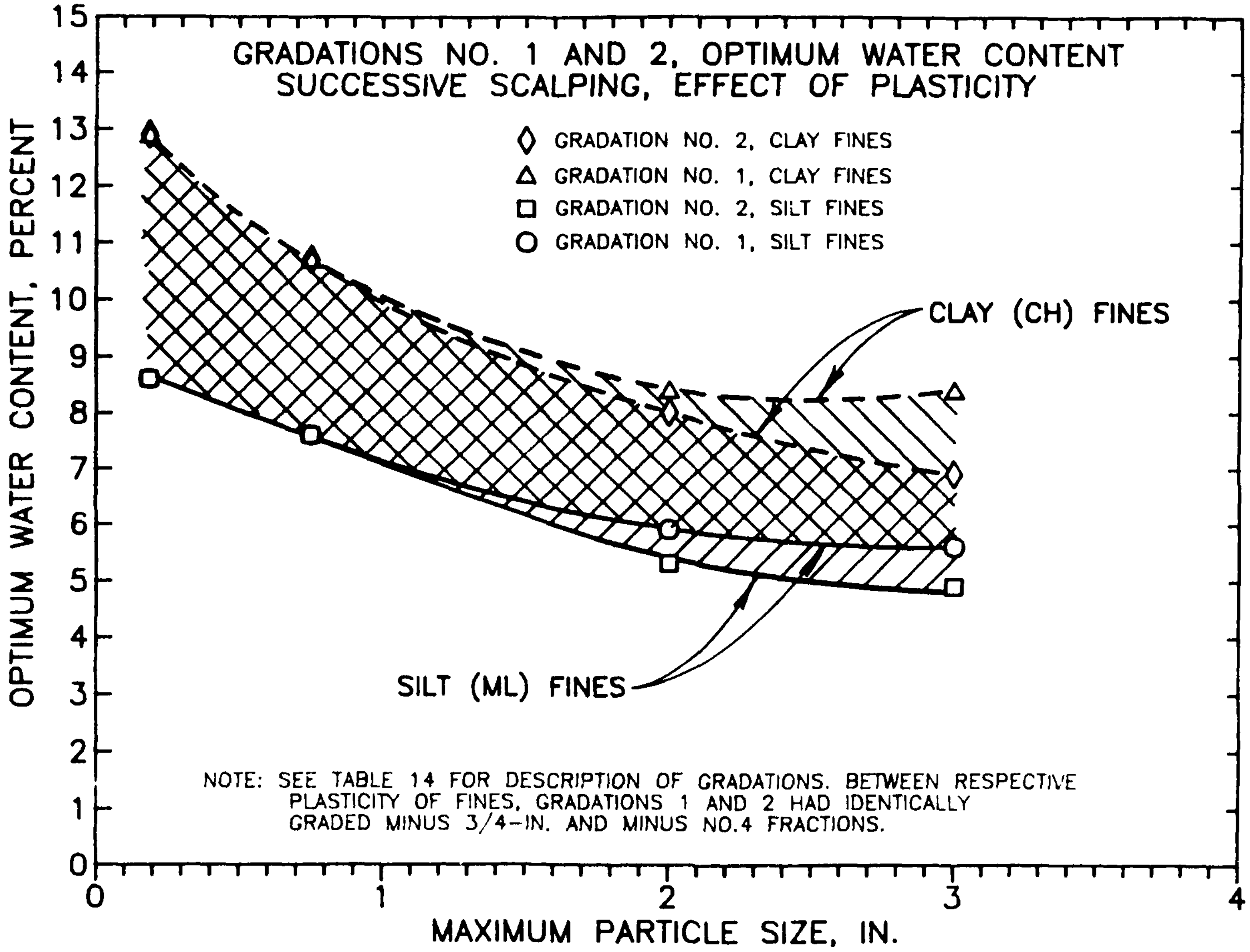


Figure 153. Optimum water content versus maximum particle size, effects of plasticity of fines, gradations Nos. 1 and 2

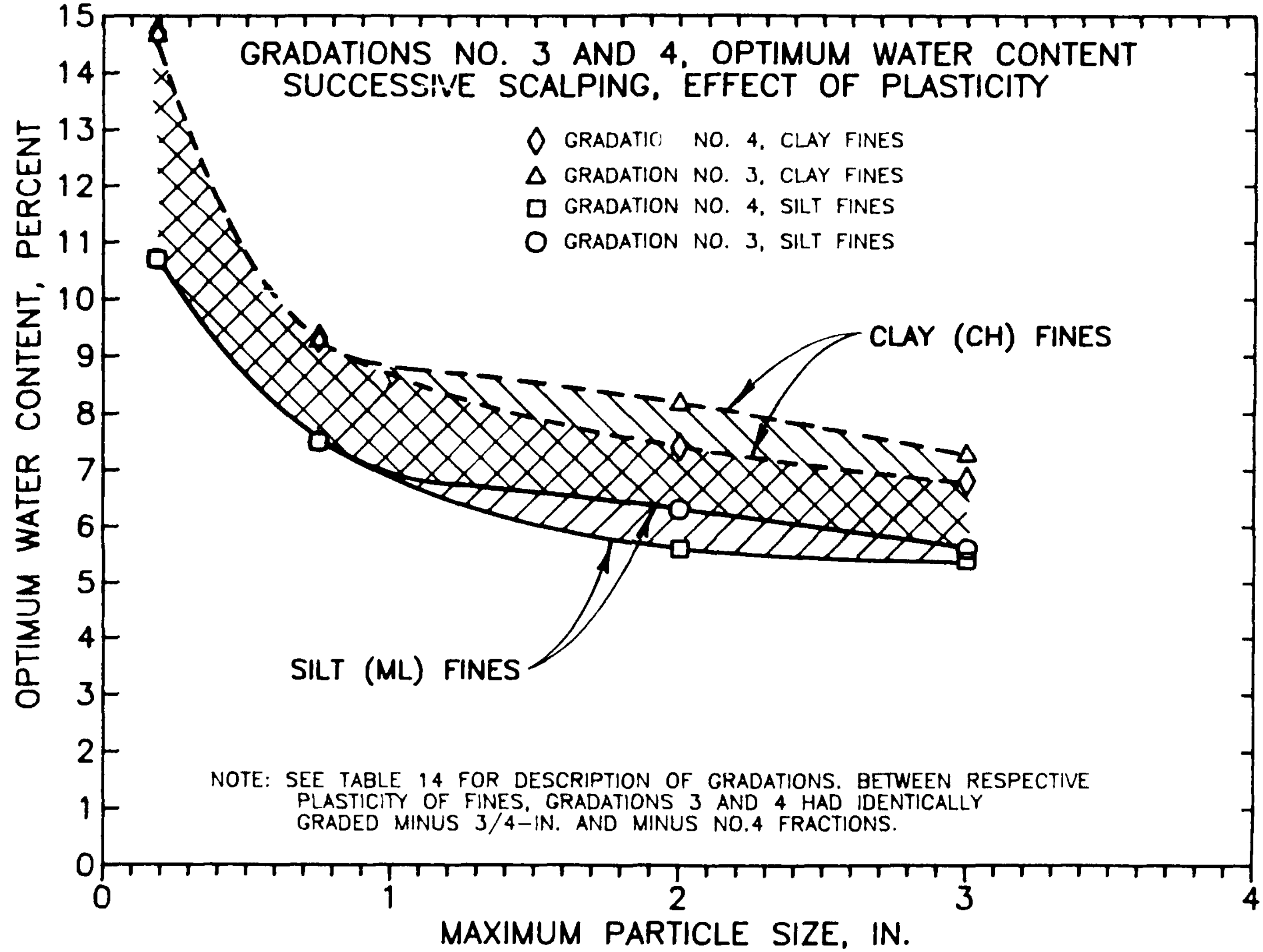


Figure 154. Optimum water content versus maximum particle size, effects of plasticity of fines, gradations Nos. 3 and 4

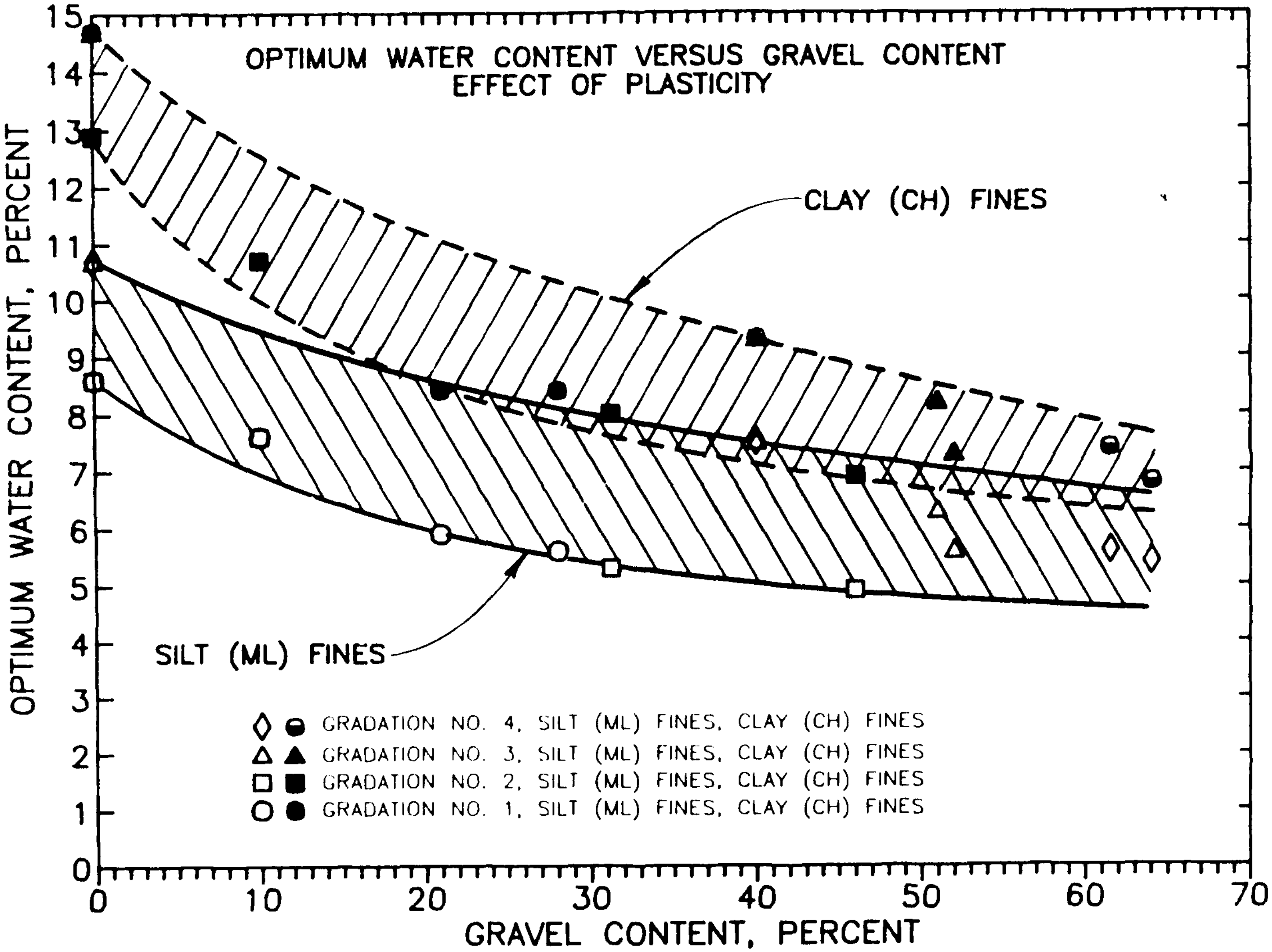


Figure 155. Optimum water content versus gravel content, effects of plasticity of fines, all test gradations

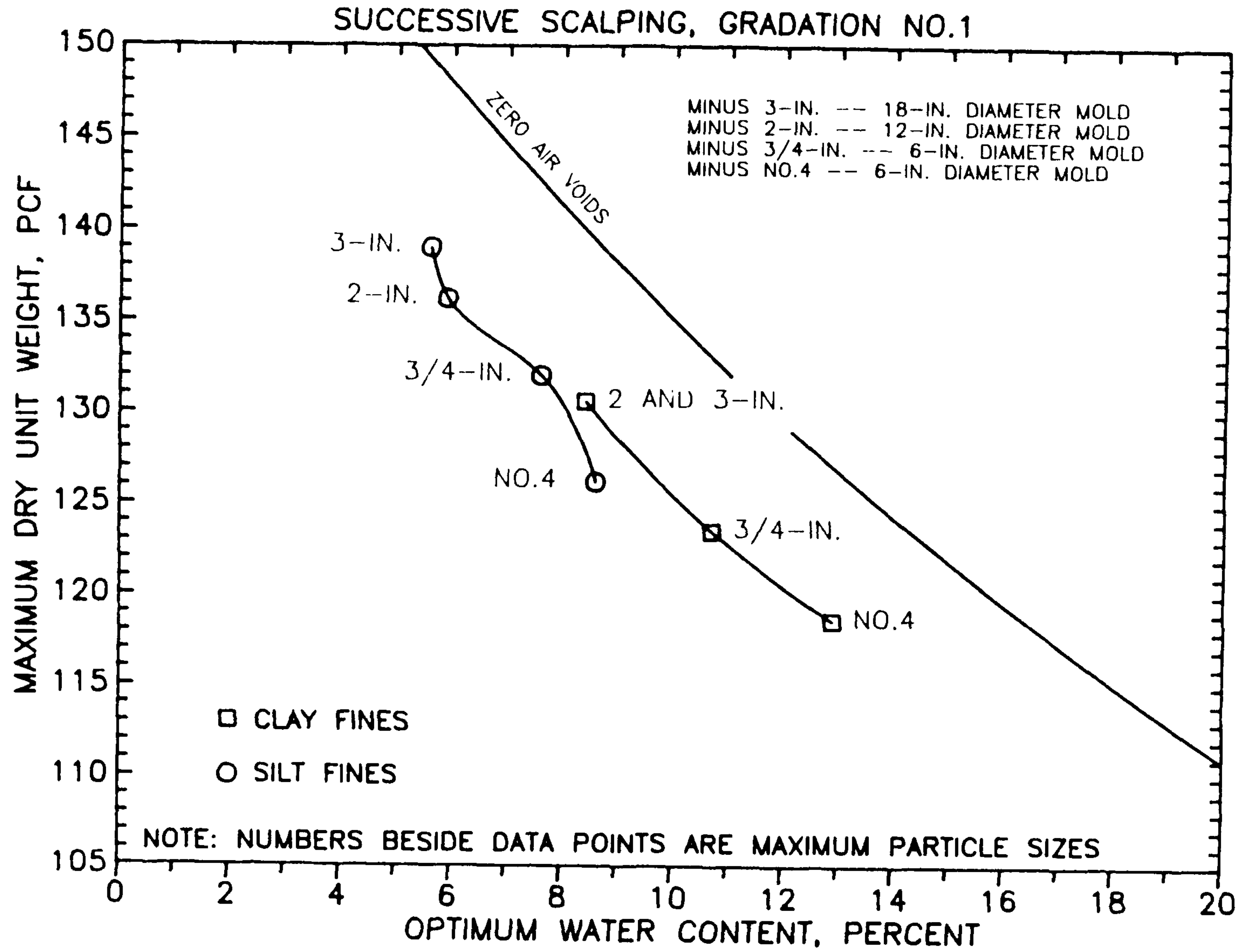


Figure 156. Maximum dry unit weight versus optimum water content, gradation No. 1, silt (ML) and clay (CH) fines

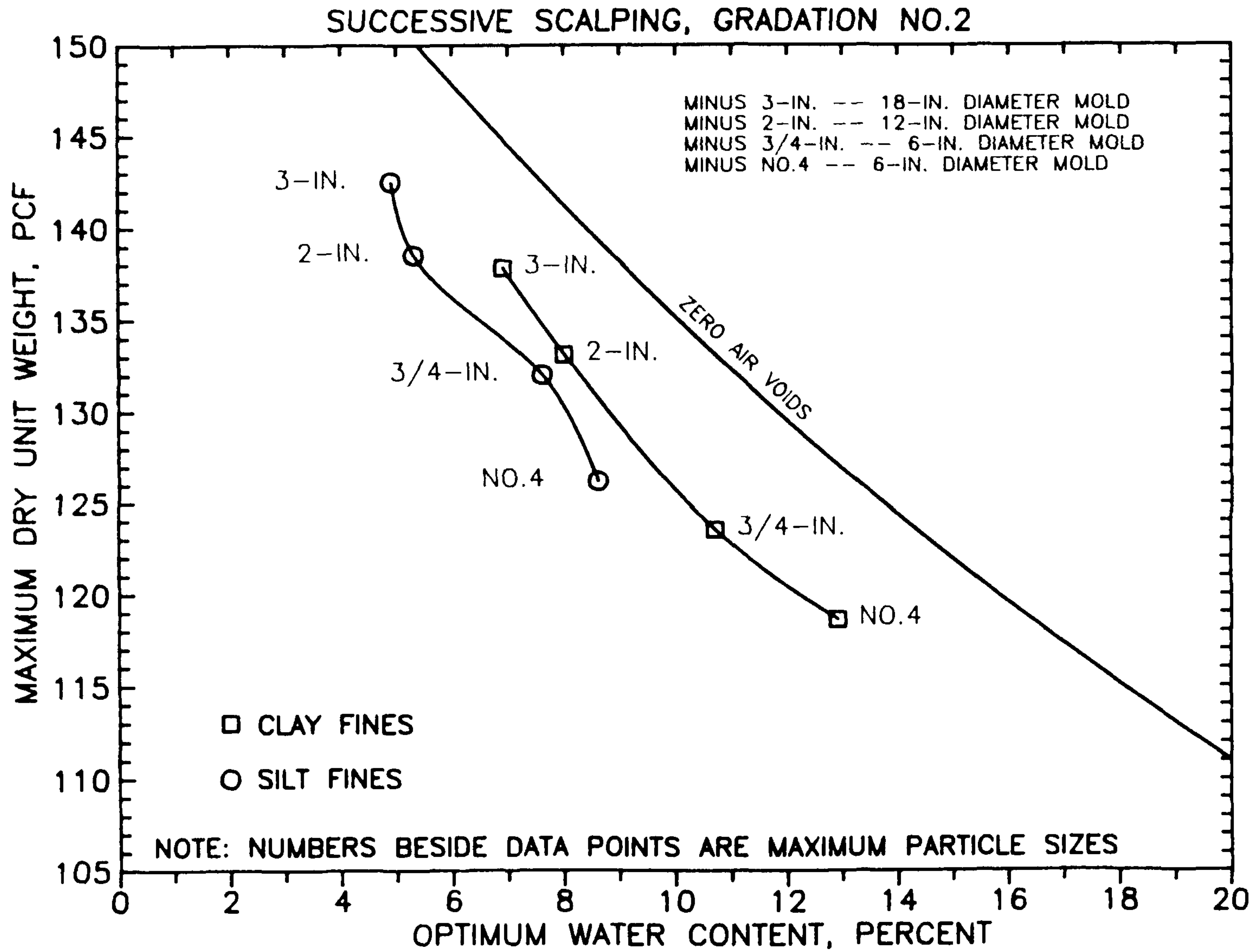


Figure 157. Maximum dry unit weight versus optimum water content, gradation No.2, silt (ML) and clay (CH) fines

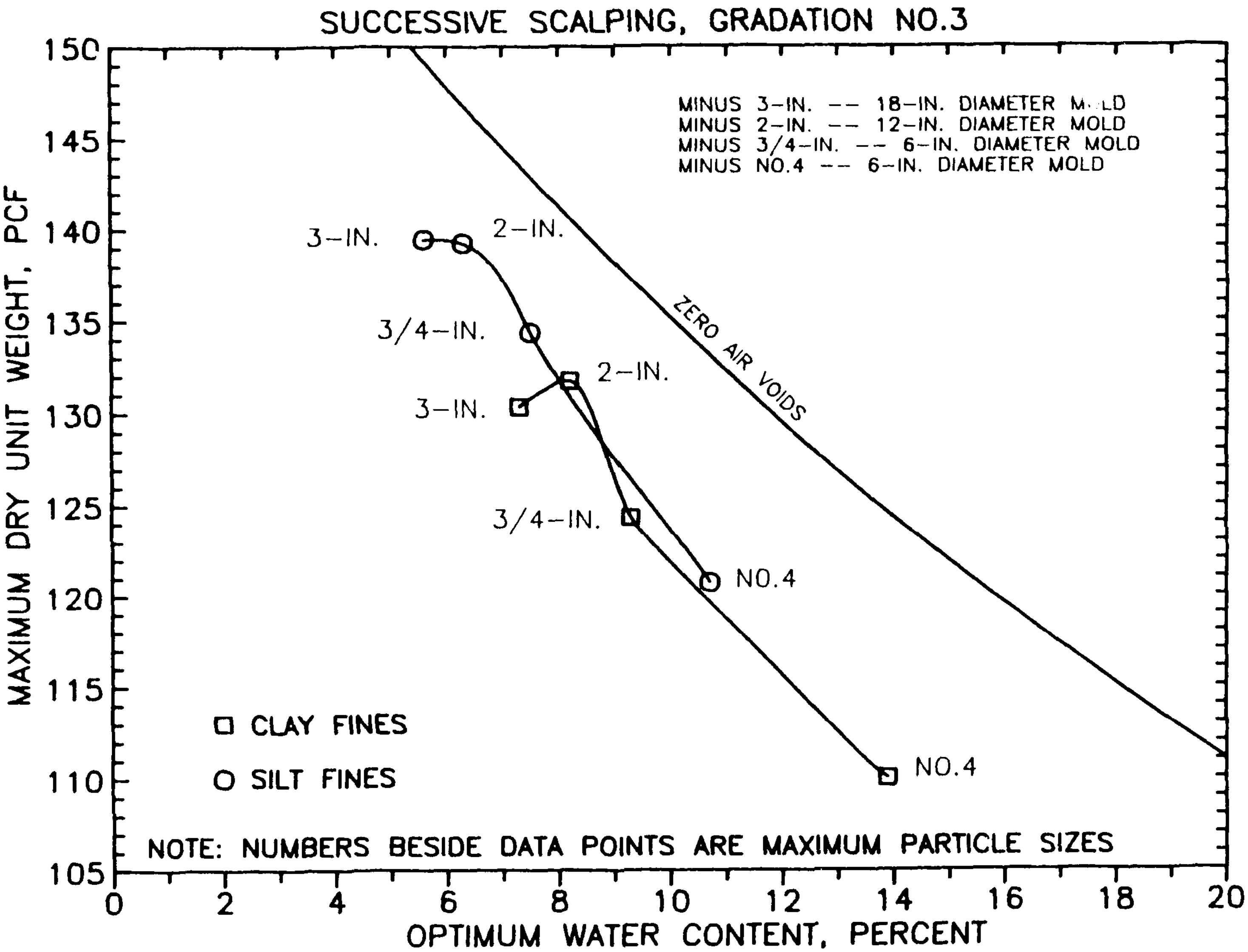


Figure 158. Maximum dry unit weight versus optimum water content, gradation No. 3 silt (ML) and clay (CH) fines

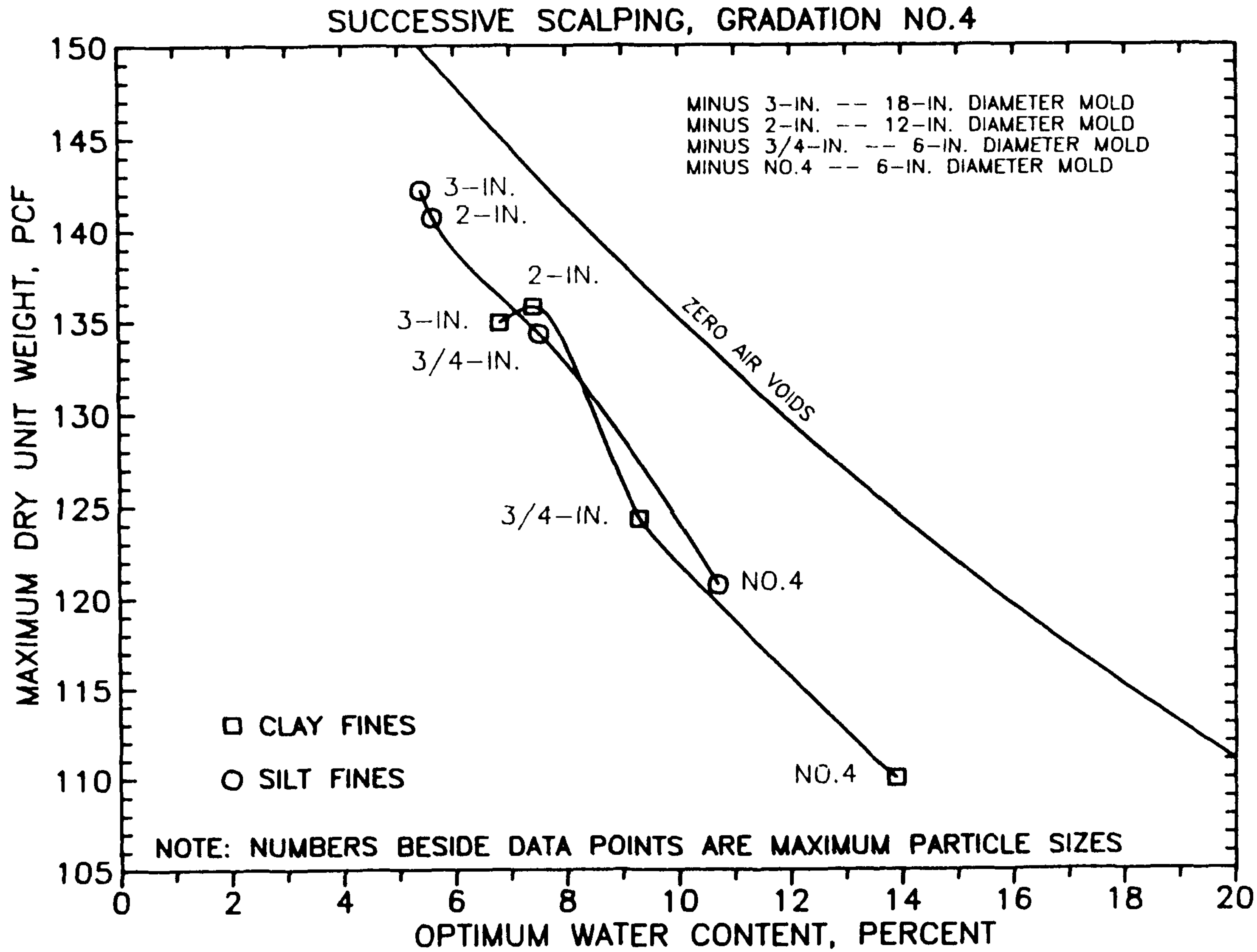


Figure 159. Maximum dry unit weight versus optimum water content, gradation No.4 silt (ML) and clay (CH) fines

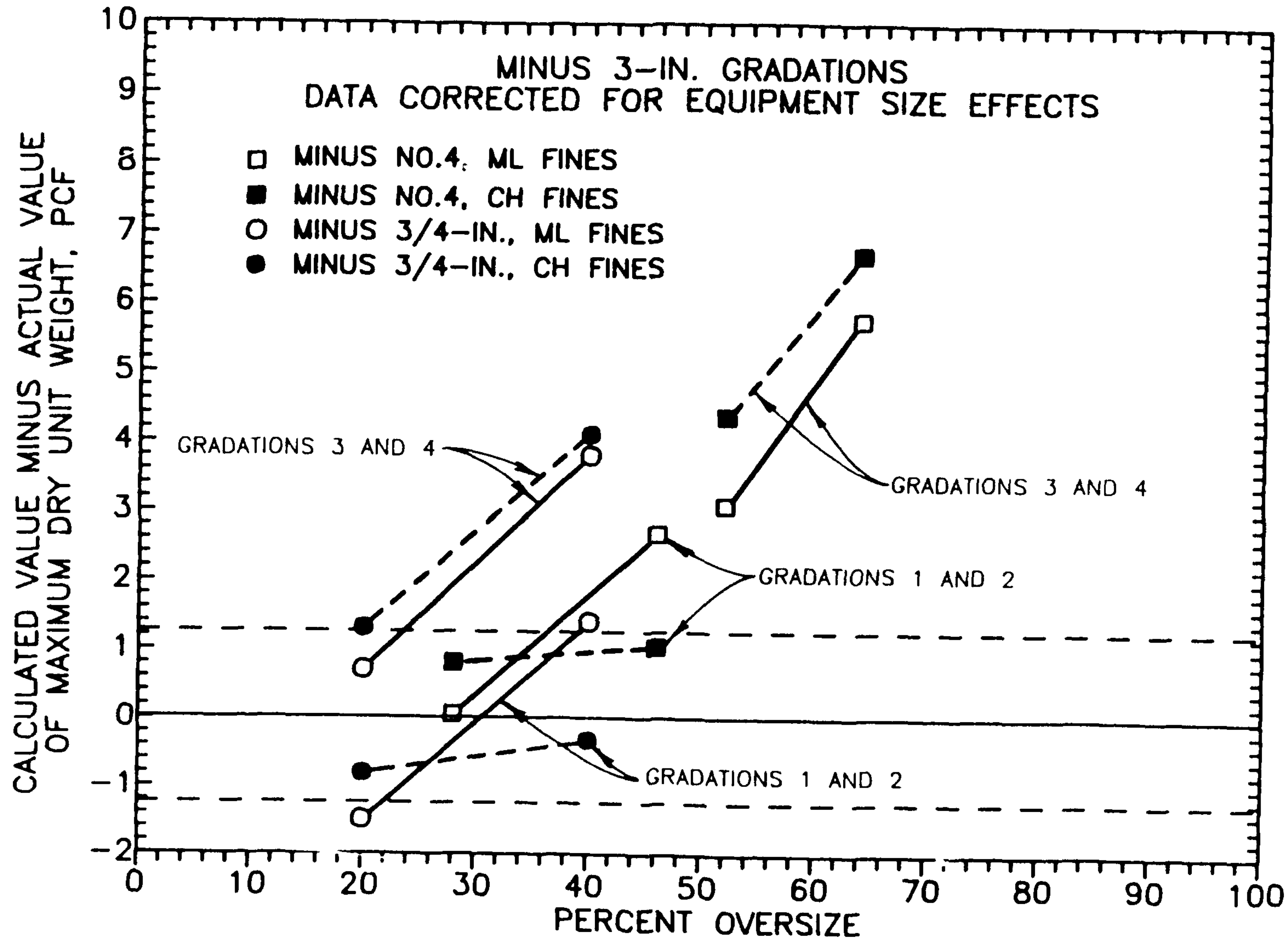


Figure 160. Predictions of maximum dry unit weights of minus 3-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize, data corrected for equipment size effects

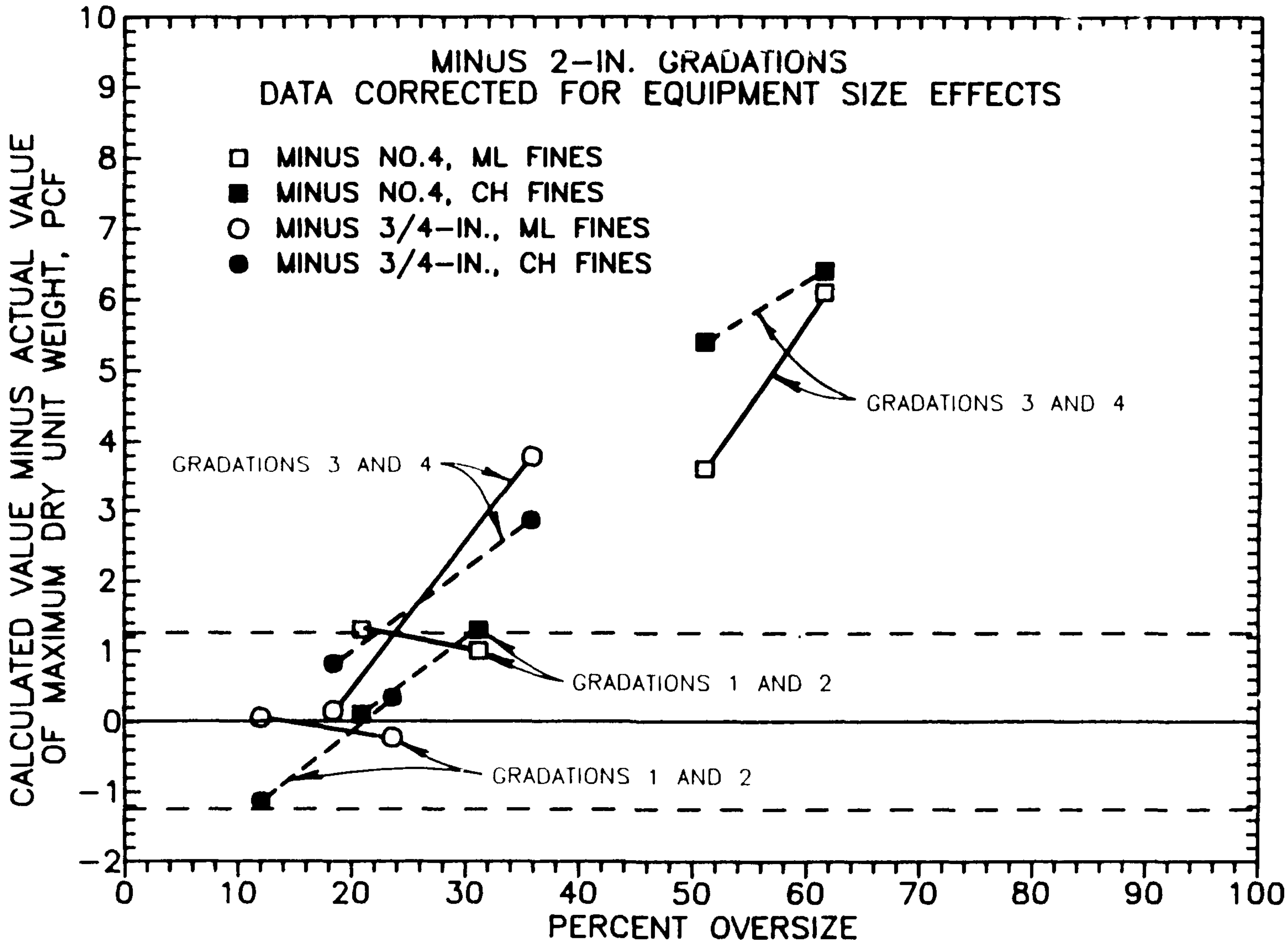


Figure 161. Predictions of maximum dry unit weights of minus 2-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize, data corrected for equipment size effects

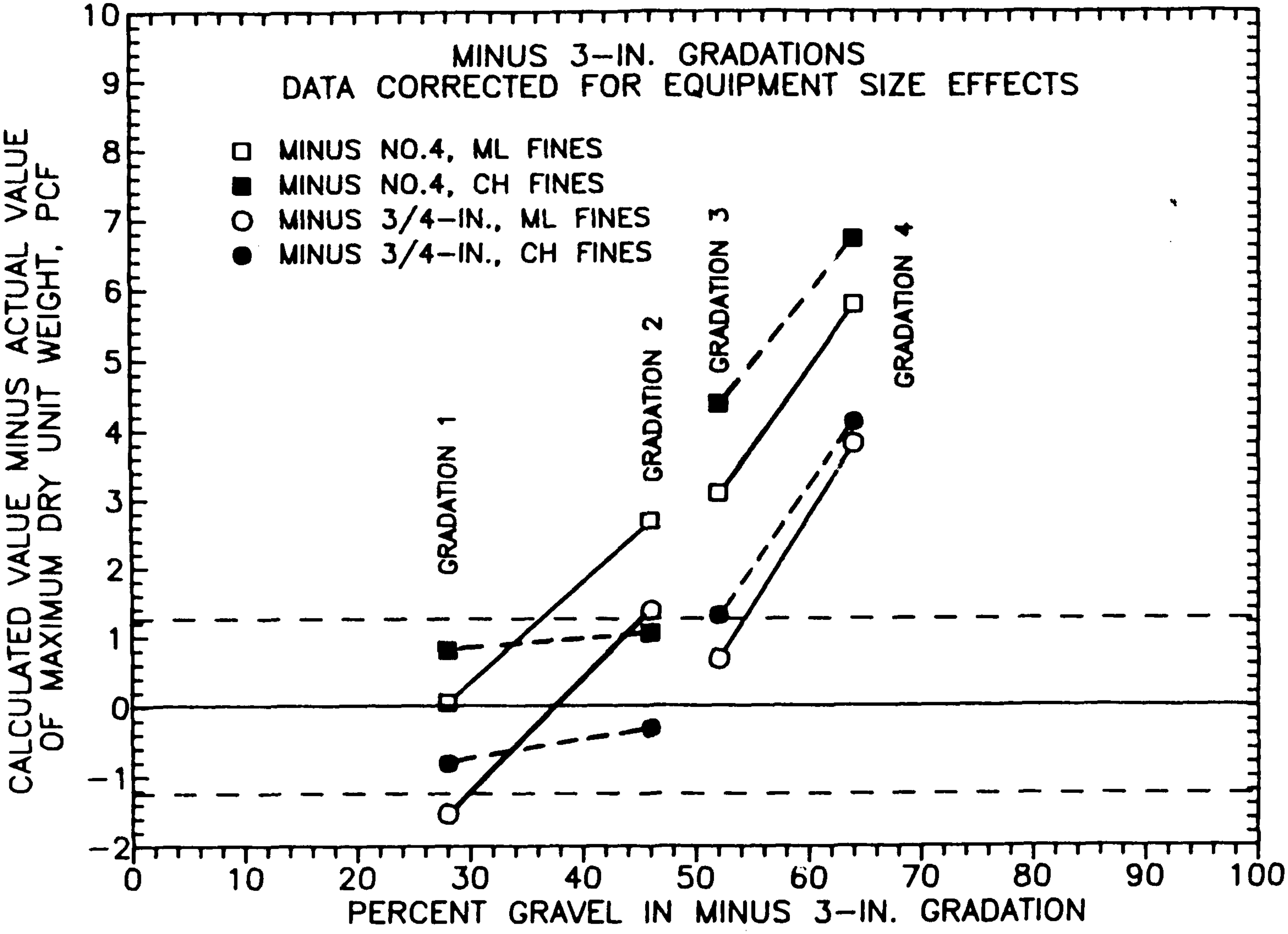


Figure 162. Predictions of maximum dry unit weights of minus 3-in. gradations versus percent gravel in the parent gradation, data corrected for equipment size effects

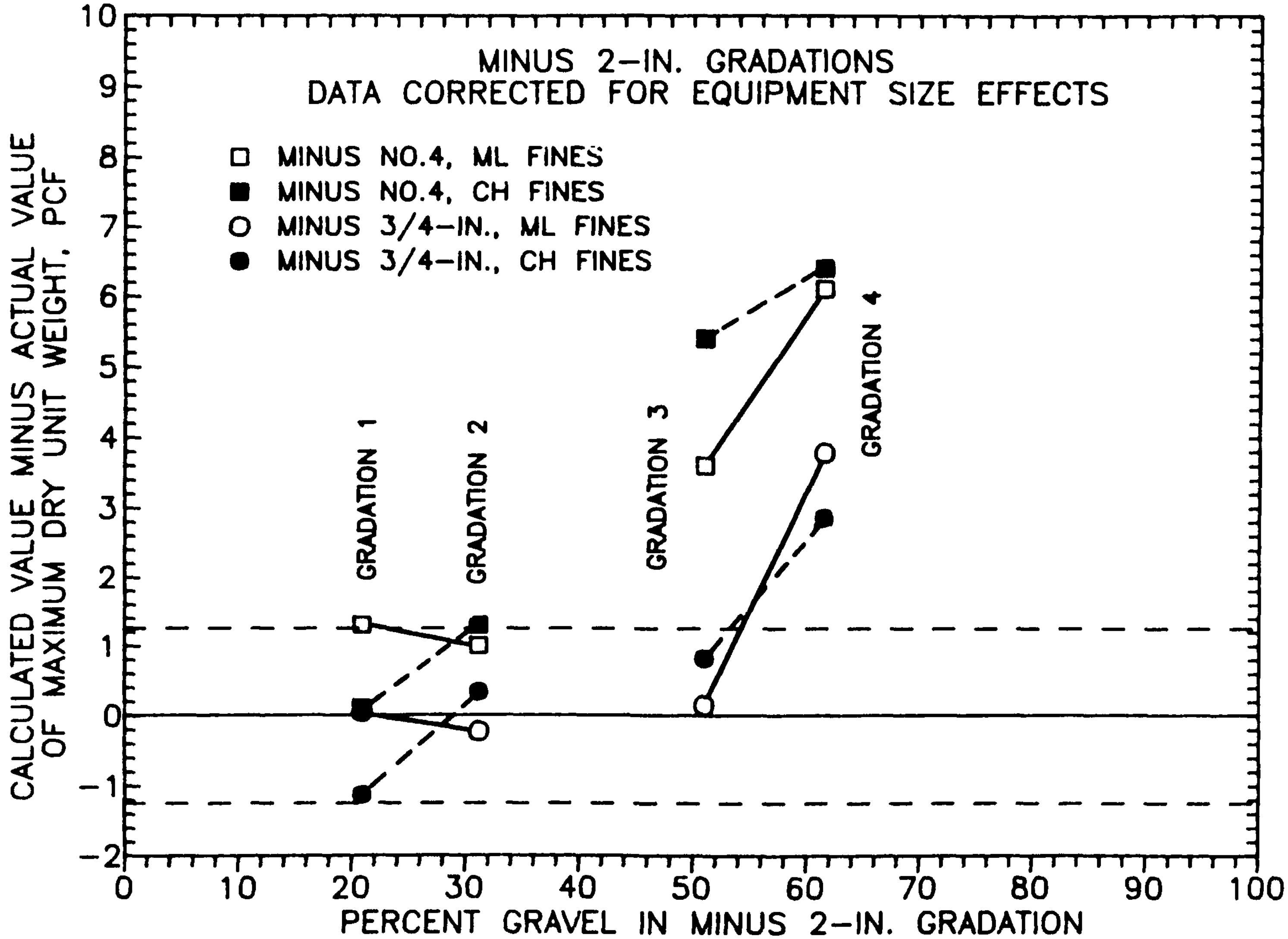


Figure 163. Predictions of maximum dry unit weights of minus 2-in. gradations versus percent gravel in the parent gradation, data corrected for equipment size effects

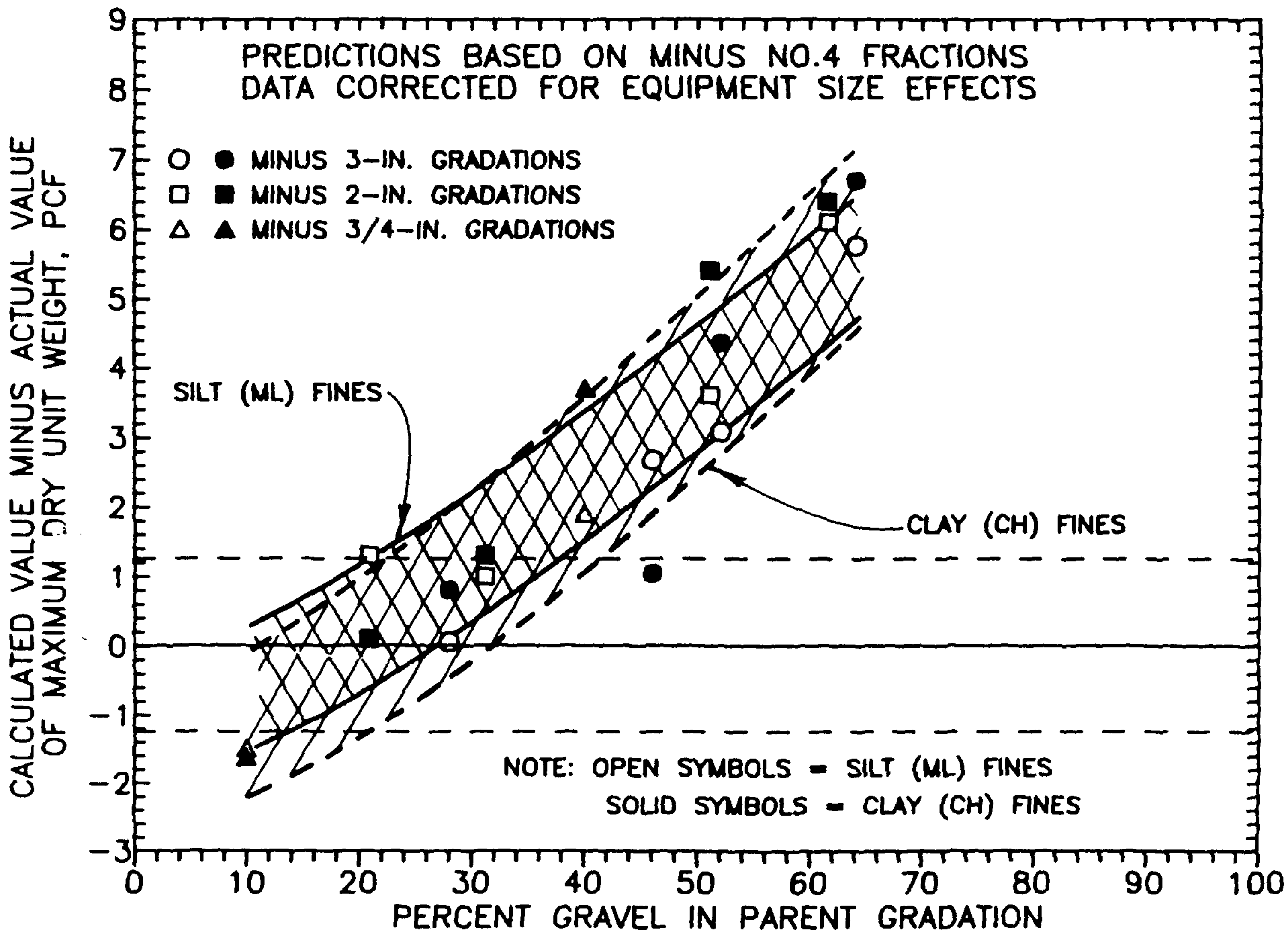


Figure 164. Summary plot for predictions of maximum dry unit weights from those of minus No.4 fractions versus percent gravel in the parent gradation, data corrected for equipment size effects

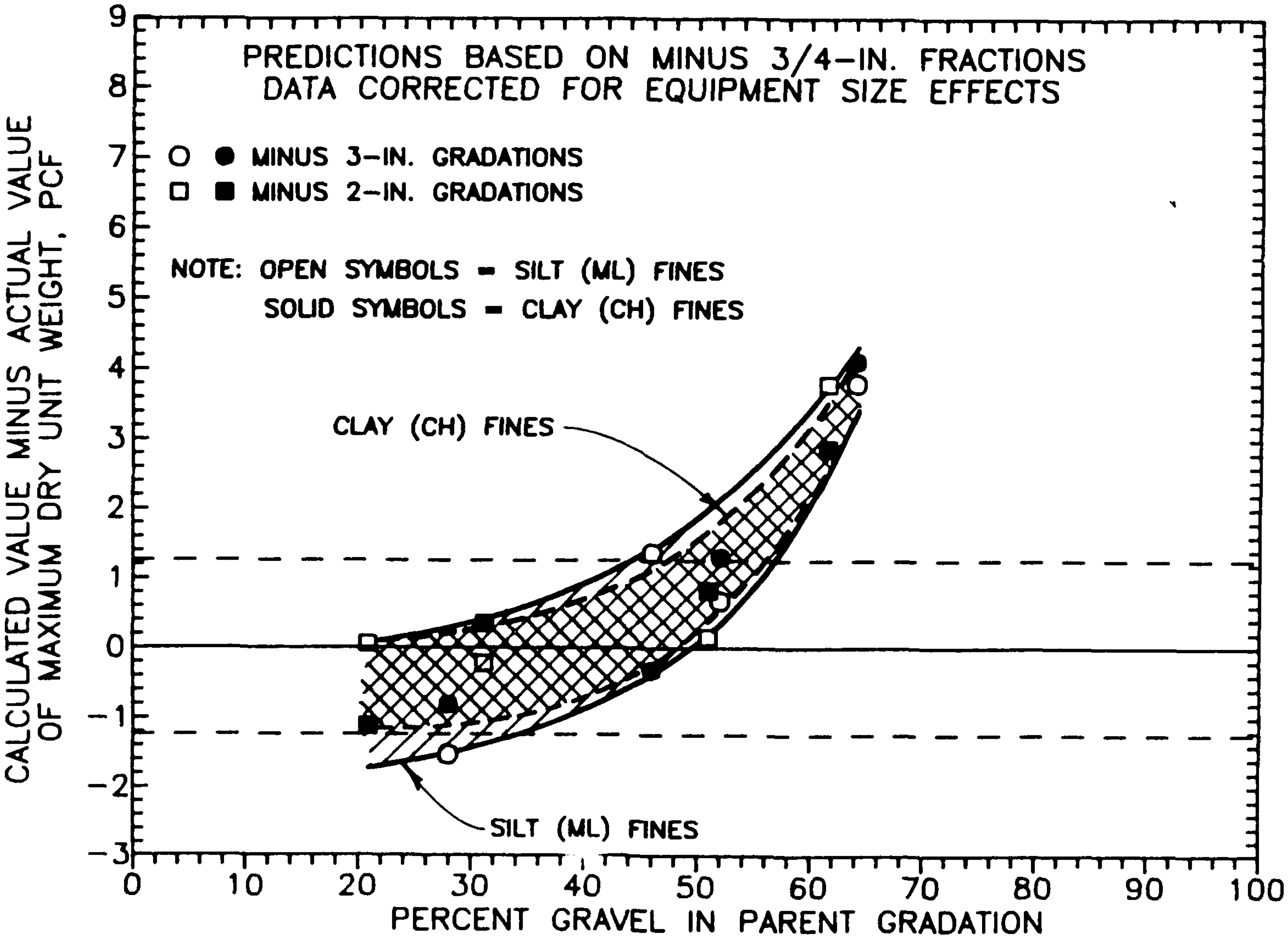


Figure 165. Summary plot for predictions of maximum dry unit weights from those of minus 3/4-in. fractions versus percent gravel in the parent gradation, data corrected for equipment size effects

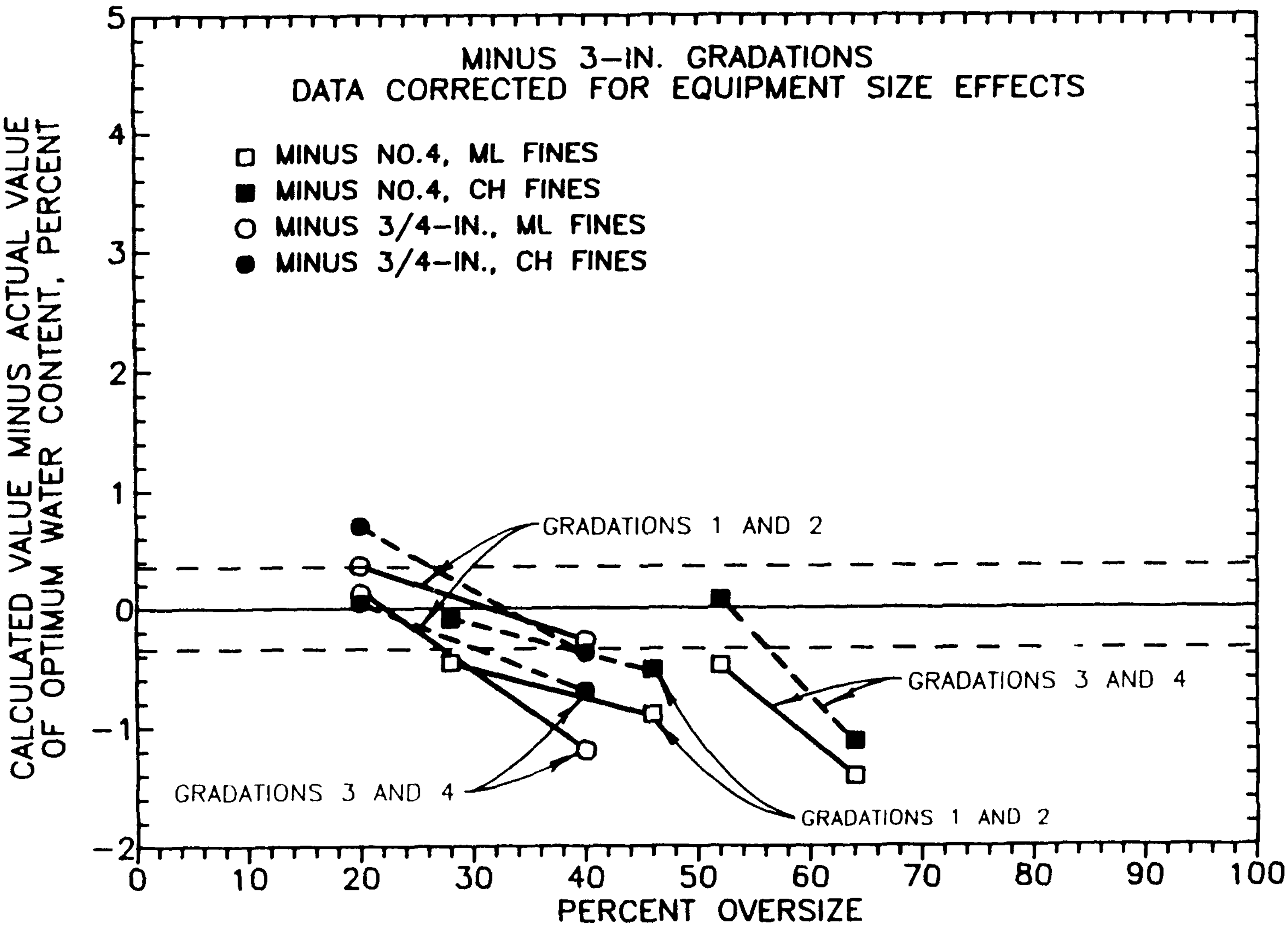


Figure 166. Predictions of optimum water contents of minus 3-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize, data corrected for equipment size effects

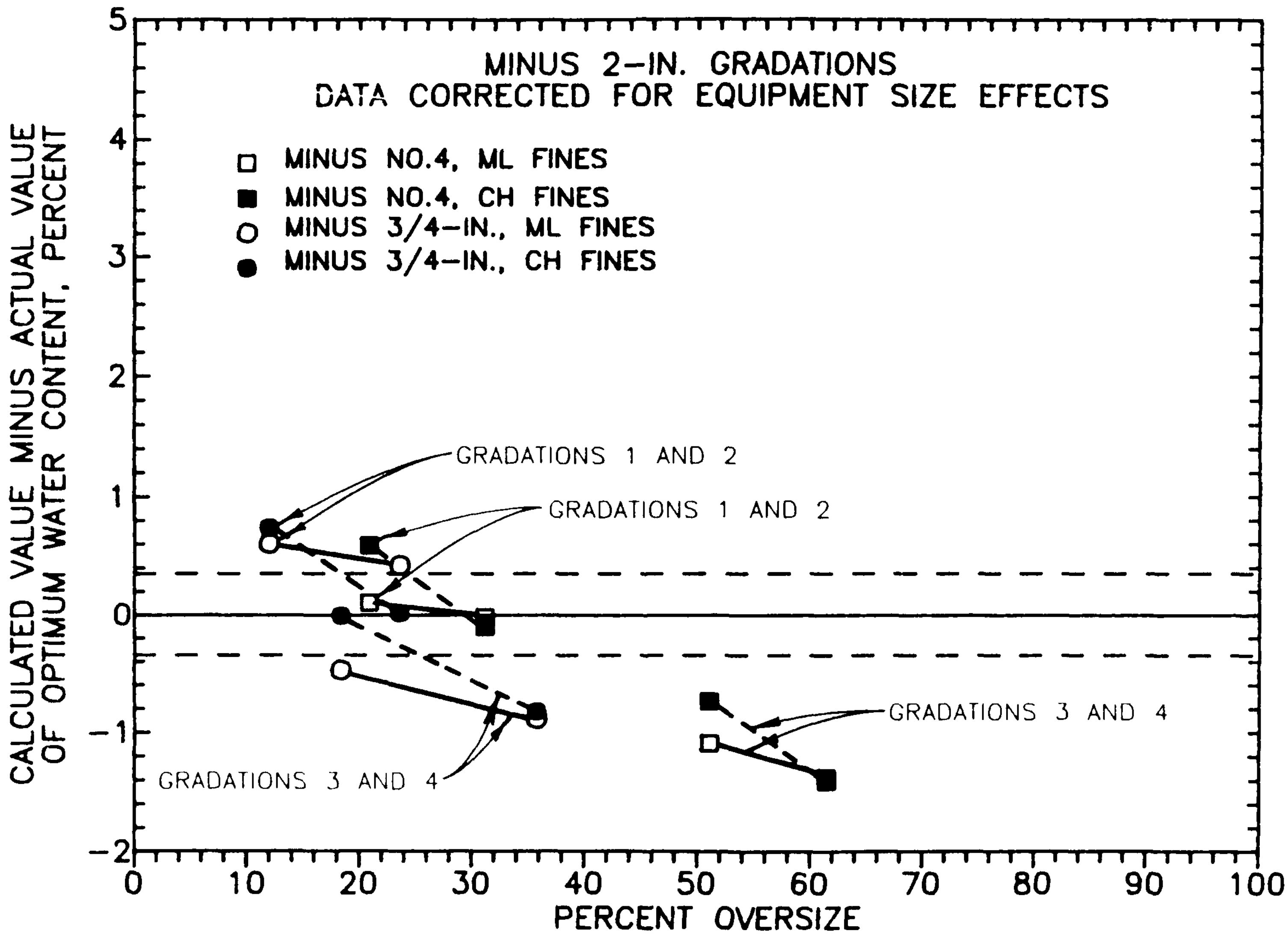


Figure 167. Predictions of optimum water contents of minus 2-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize data corrected for equipment size effects

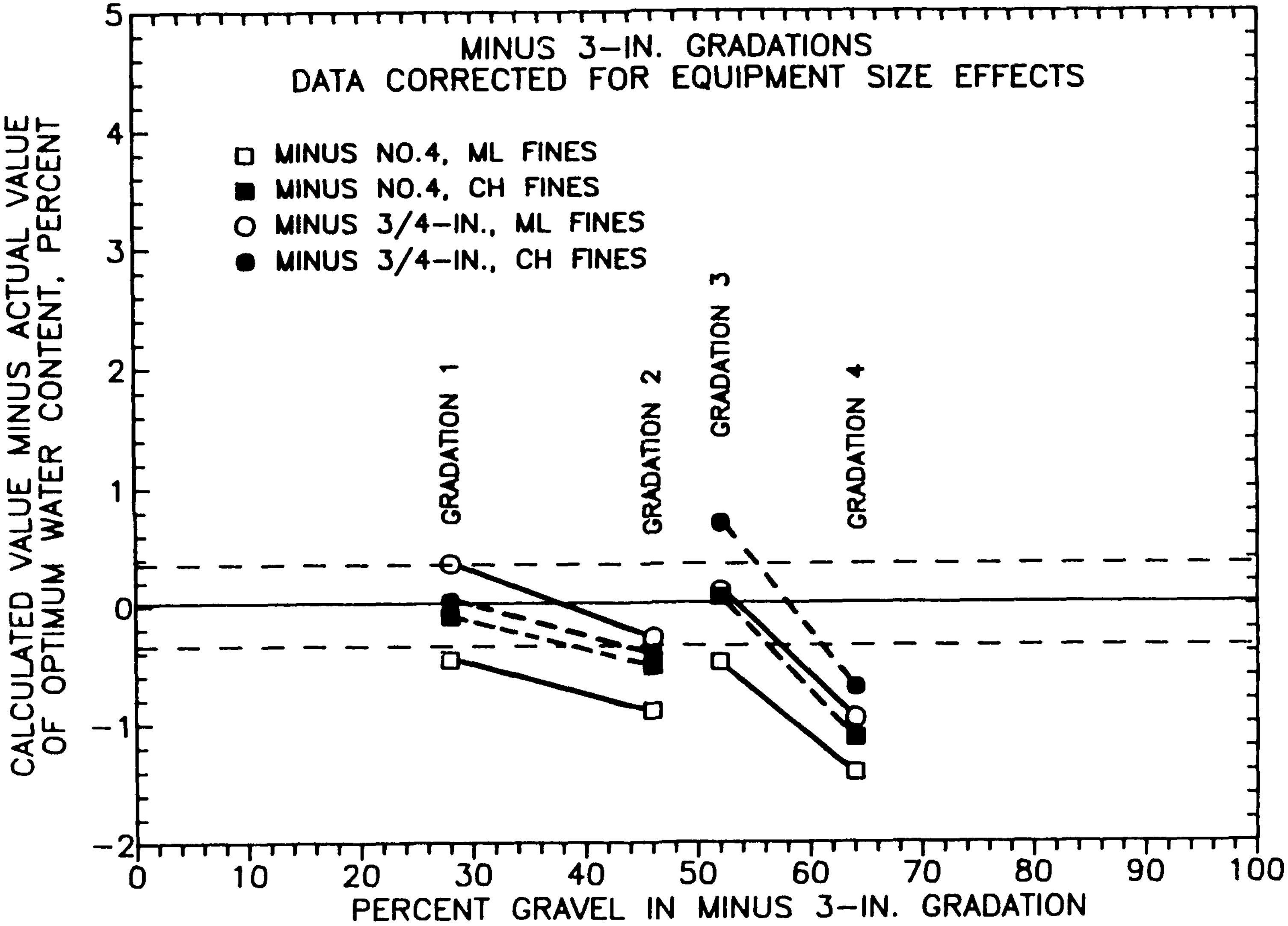


Figure 168. Predictions of optimum water contents of minus 3-in. gradations versus percent gravel in parent gradation, data corrected for equipment size effects

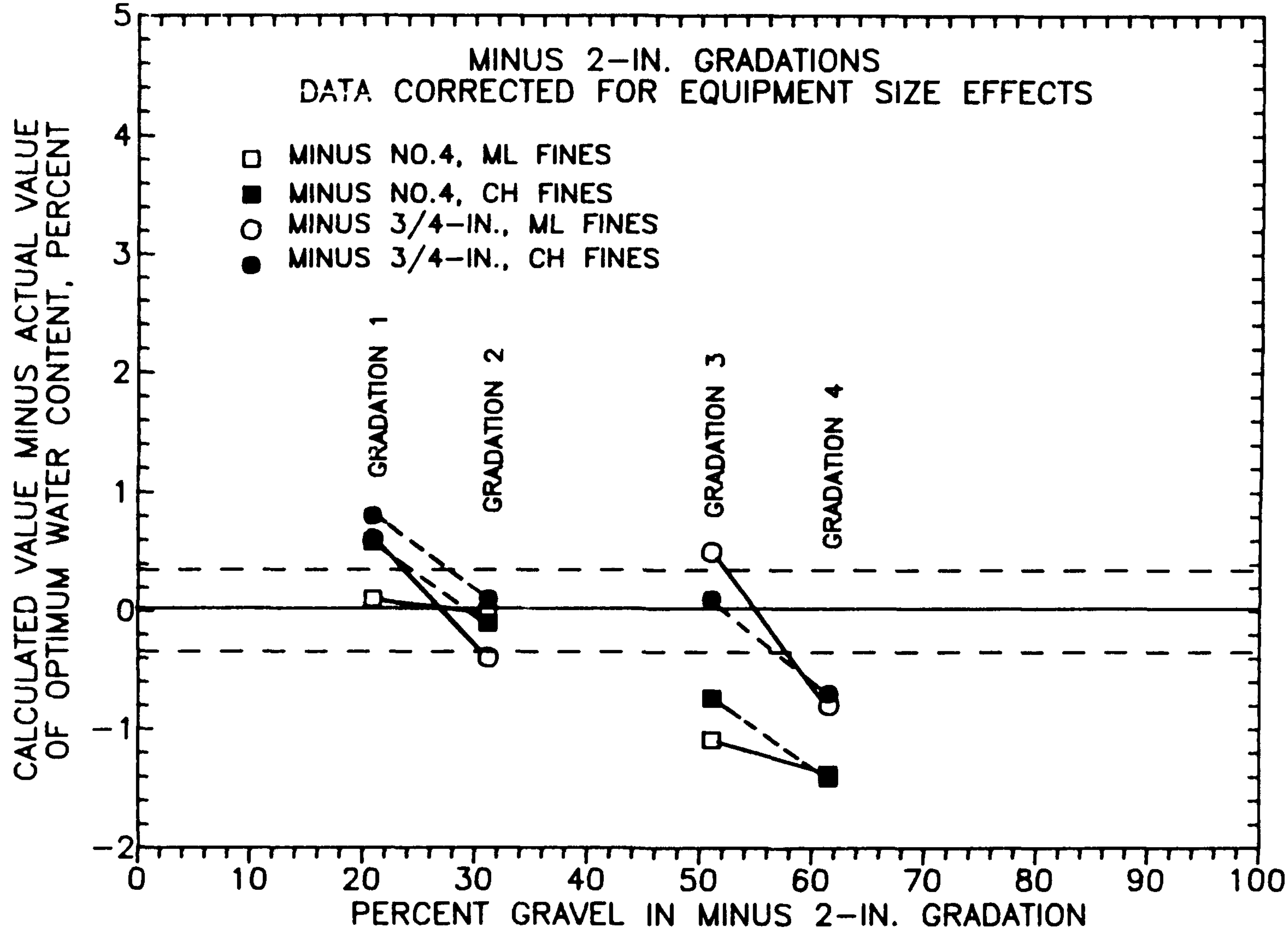


Figure 169. Predictions of optimum water contents of minus 2-in. gradations versus percent gravel in parent gradation, data corrected for equipment size effects

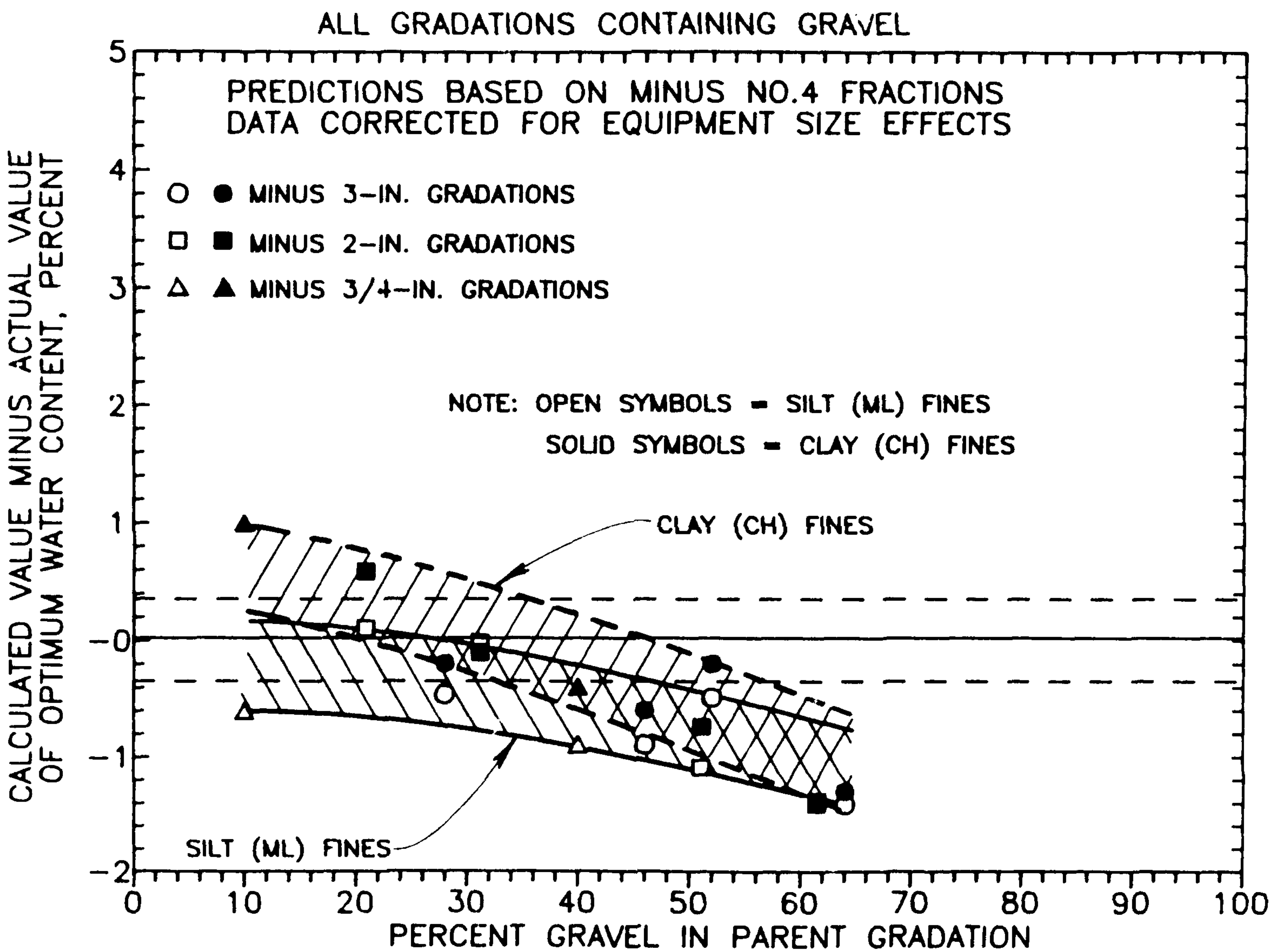


Figure 170. Summary plot for predictions of optimum water contents from those of minus No.4 fractions versus percent gravel in the parent gradation, data corrected for equipment size effects

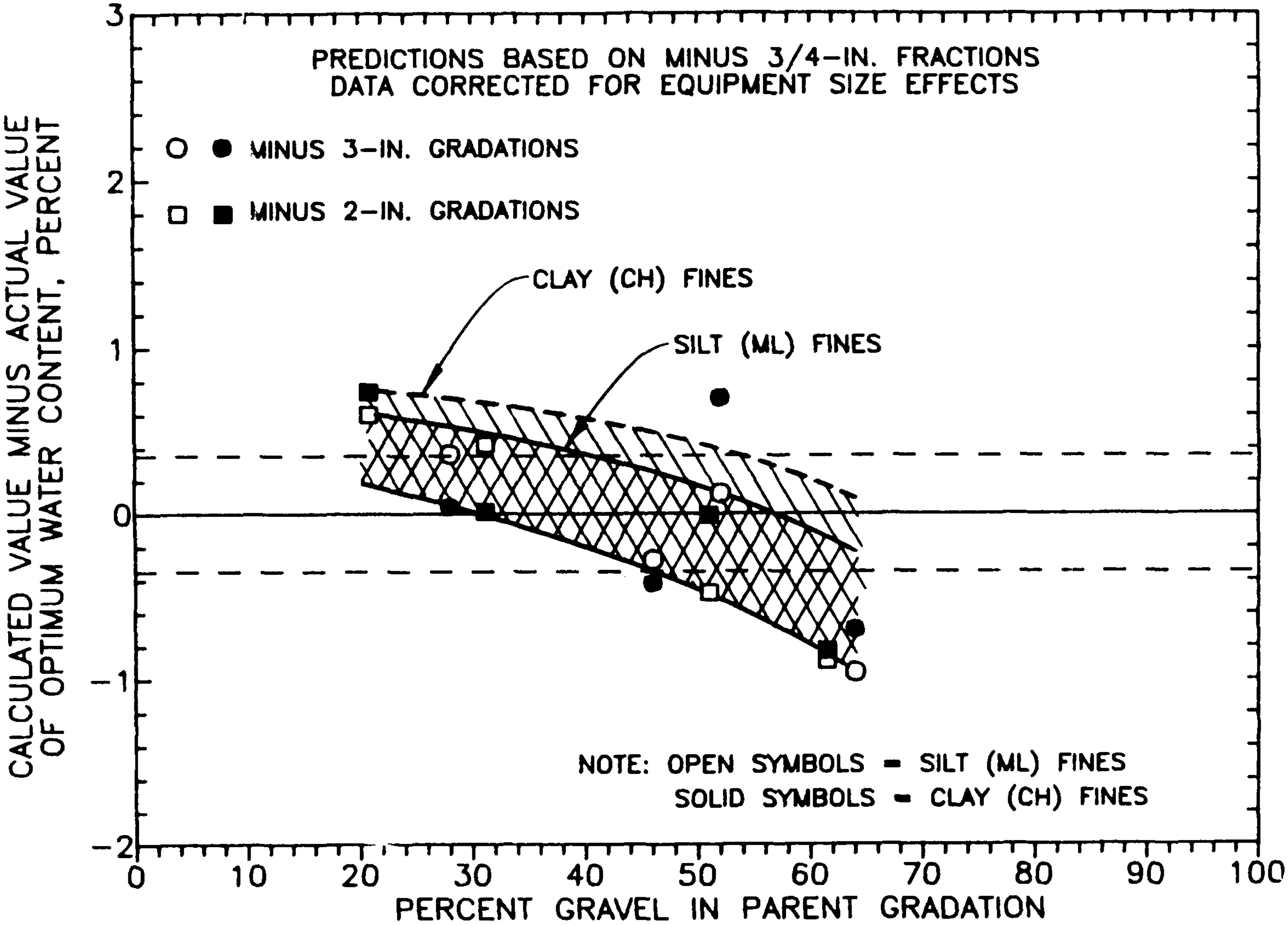


Figure 171. Summary plot for prediction of optimum water contents from those of minus 3/4-in. fractions versus percent gravel in the parent gradation, data corrected for equipment size effect

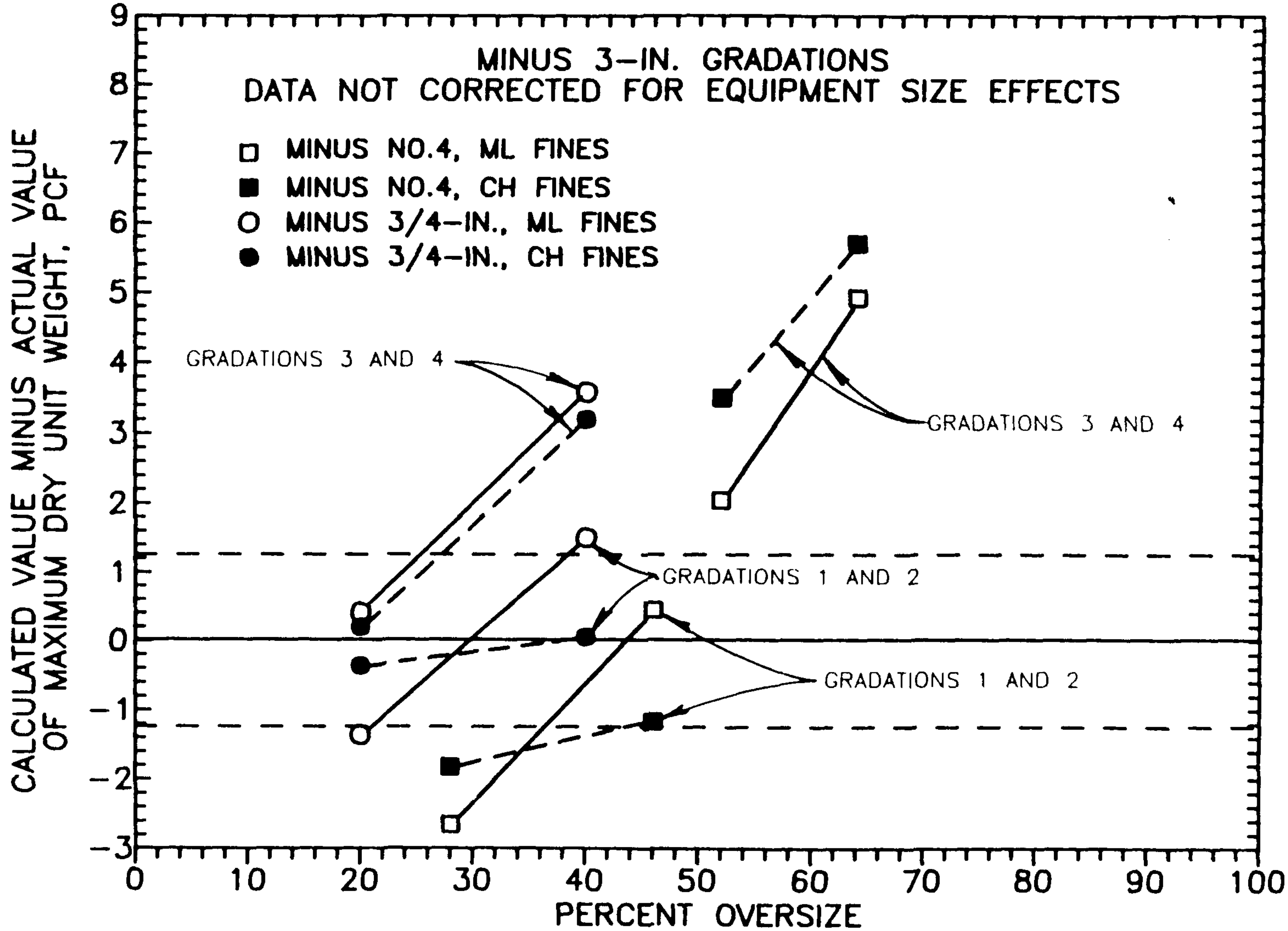


Figure 172. Predictions of maximum dry unit weights of minus 3-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize, data not corrected for equipment size effects

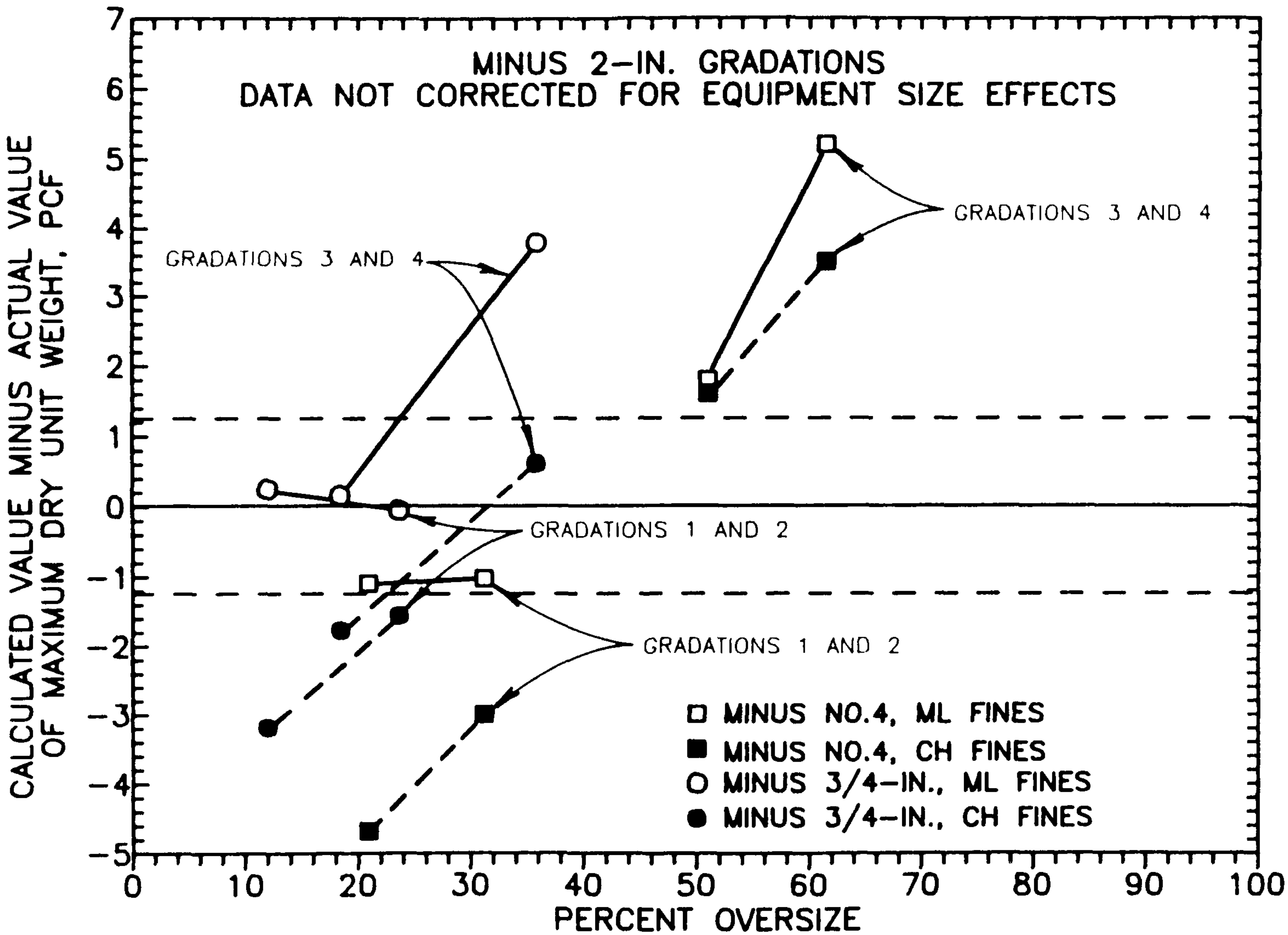


Figure 173. Predictions of maximum dry unit weights of minus 2-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize, data not corrected for equipment size effects

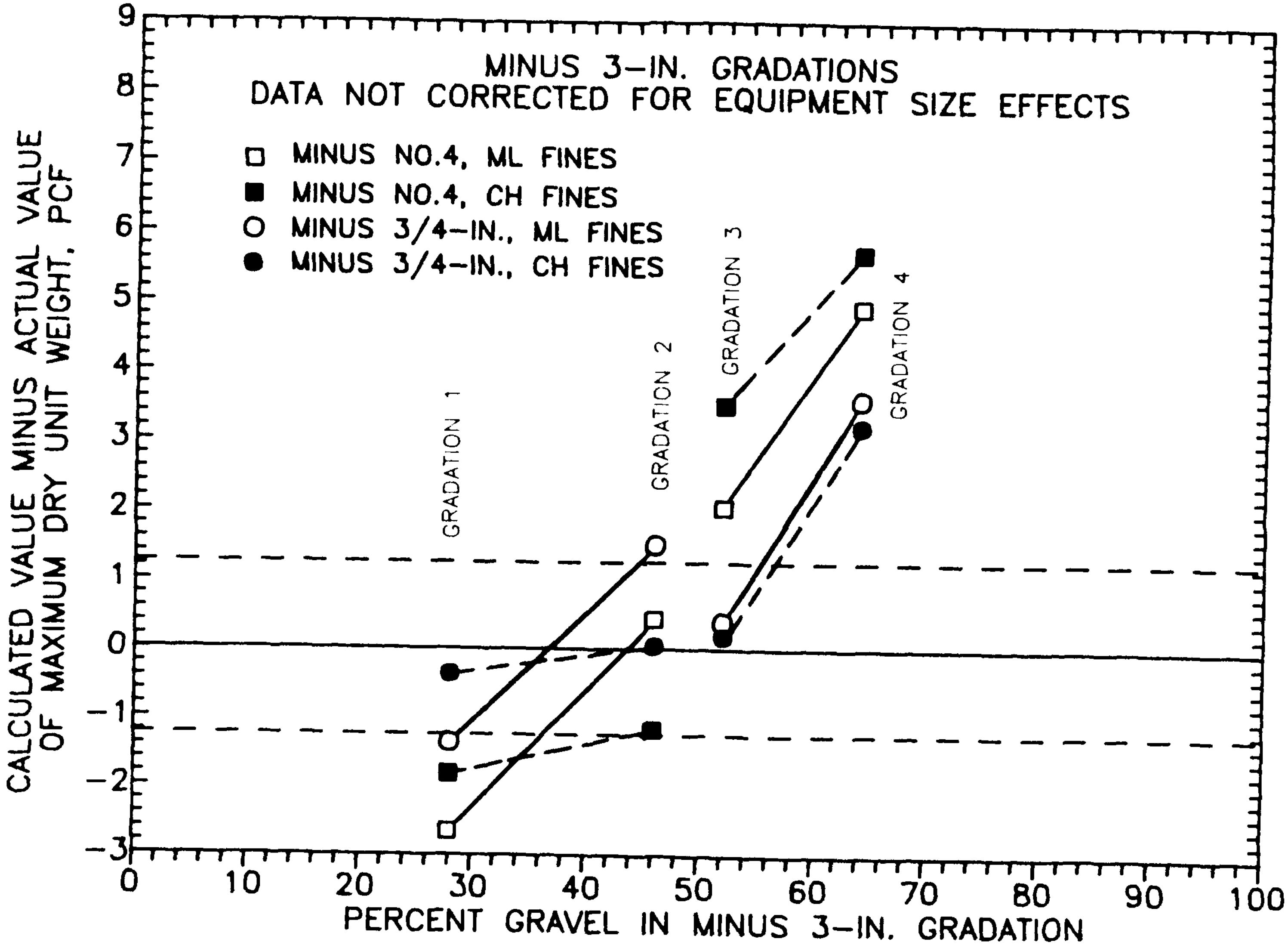


Figure 174. Predictions of maximum dry unit weights of minus 3-in. gradations versus percent gravel in the parent gradation, data not corrected for equipment size effects

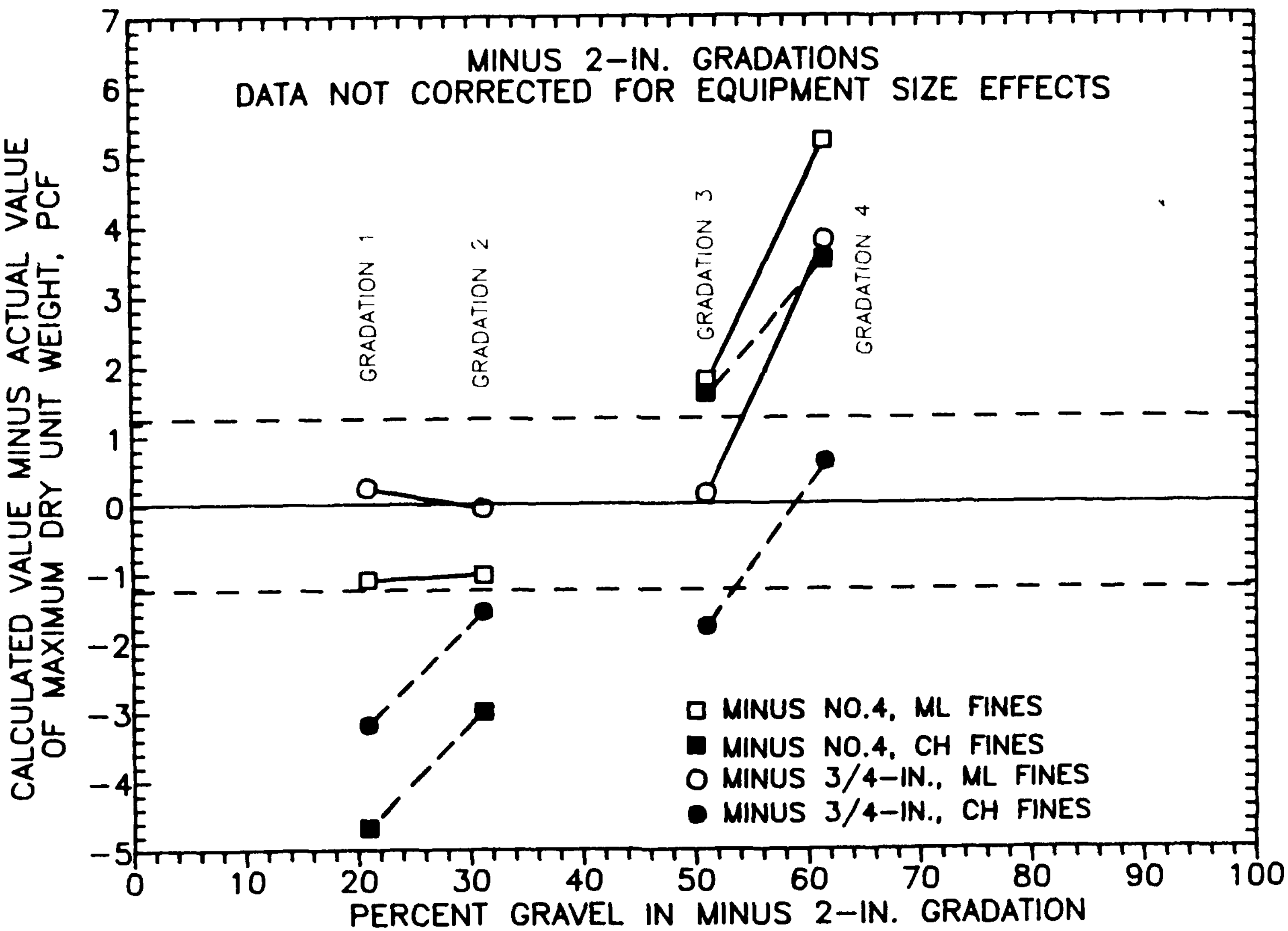


Figure 175. Predictions of maximum dry unit weights of minus 2-in. gradations versus percent gravel in the parent gradation, data not corrected for equipment size effects

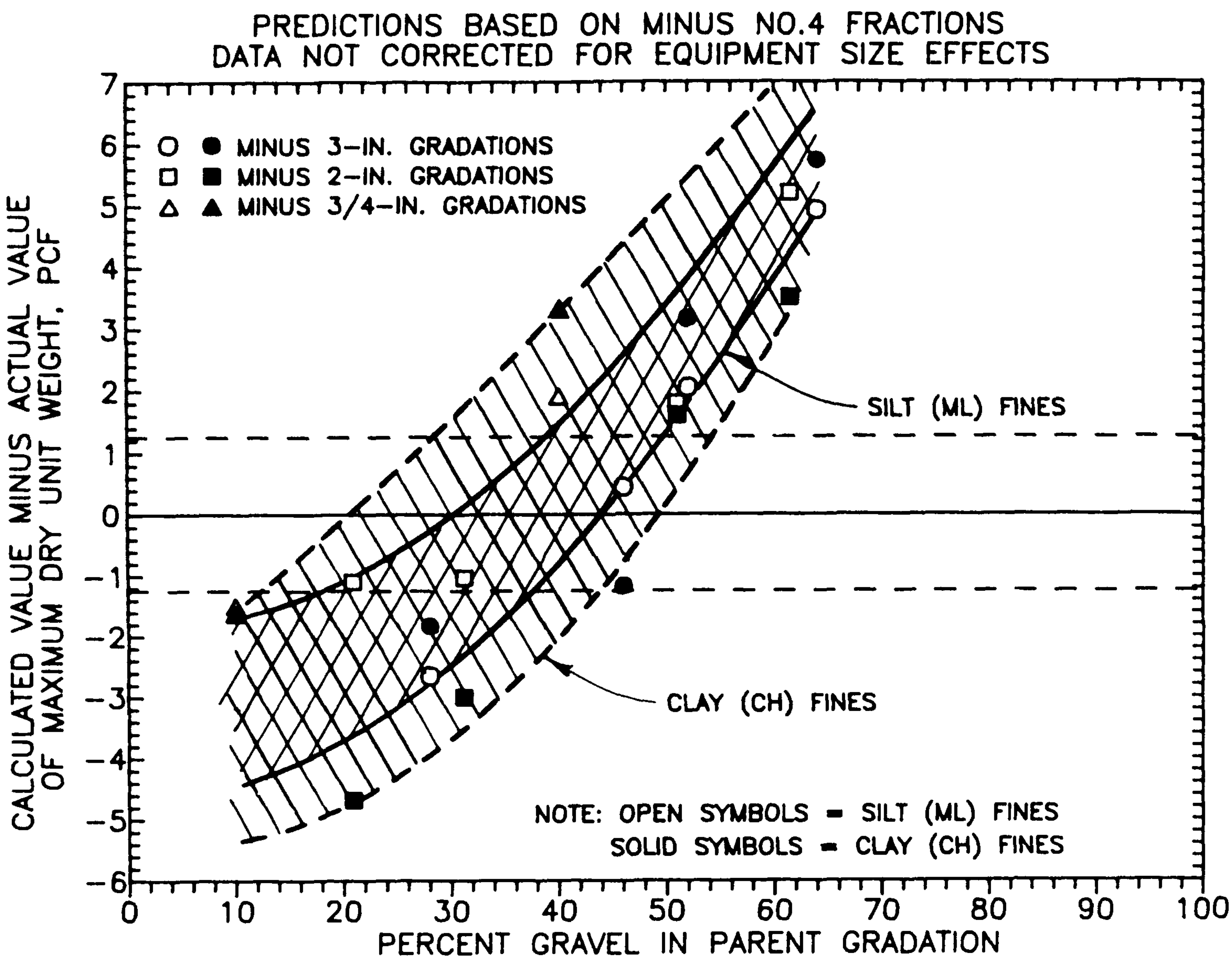


Figure 176. Summary plot for predictions of maximum dry unit weights from those of minus No.4 fractions versus percent gravel in the parent gradation, data not corrected for equipment size effects

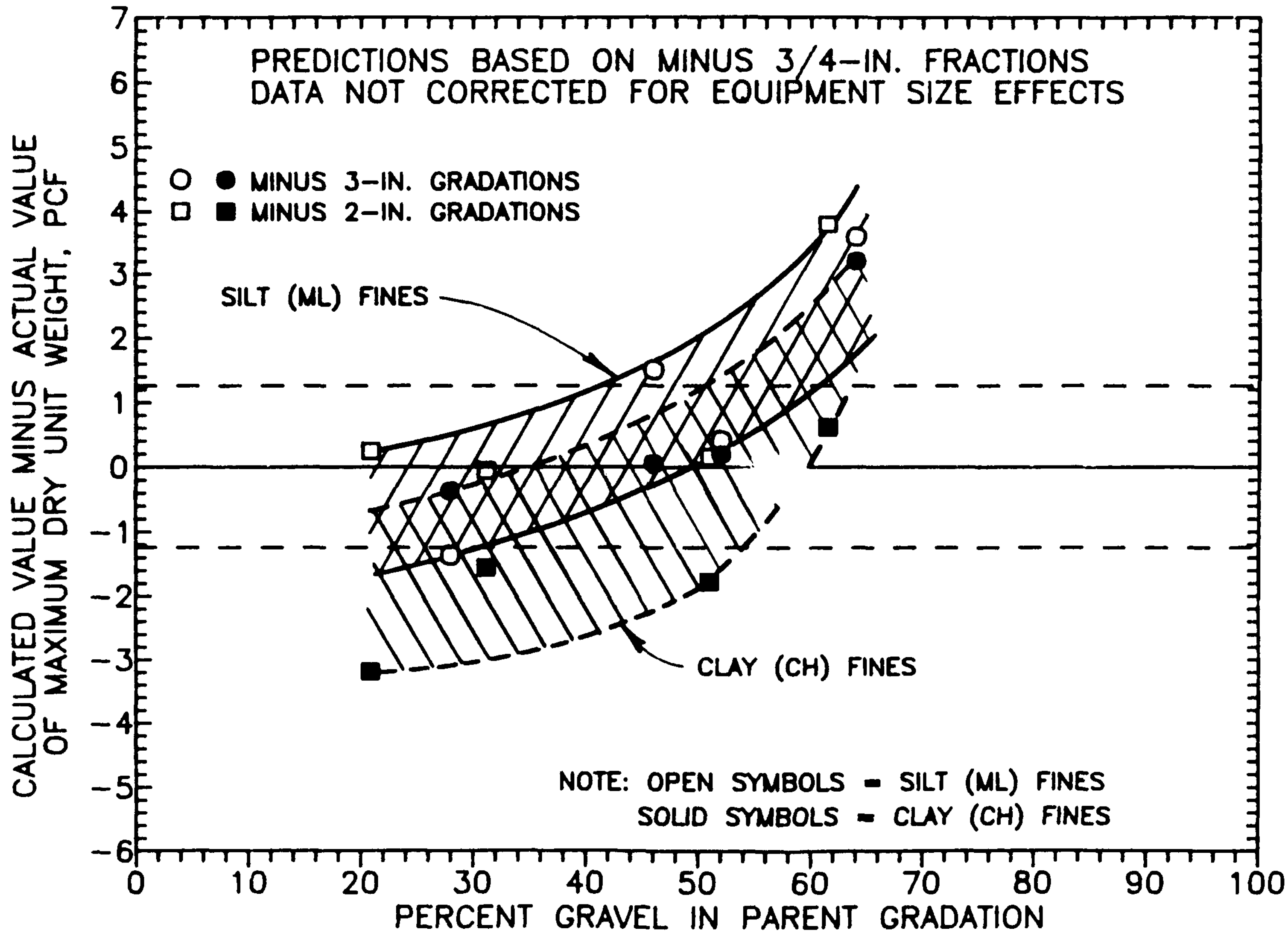


Figure 177. Summary plot for predictions of maximum dry unit weights from those of minus 3/4-in. fractions versus percent gravel in the parent gradation, data not corrected for equipment size effects

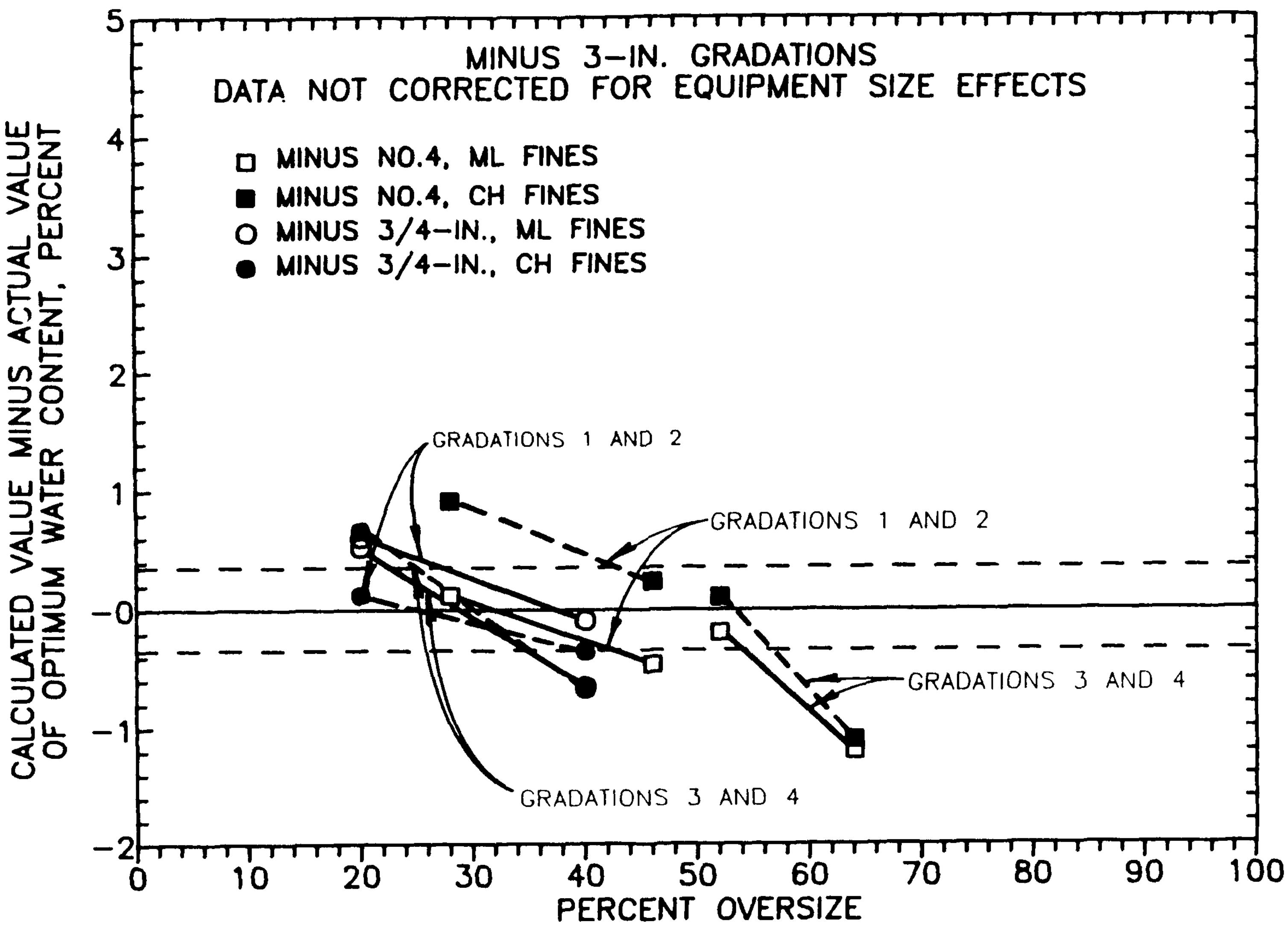


Figure 178. Predictions of optimum water contents of minus 3-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize, data not corrected for equipment size effects

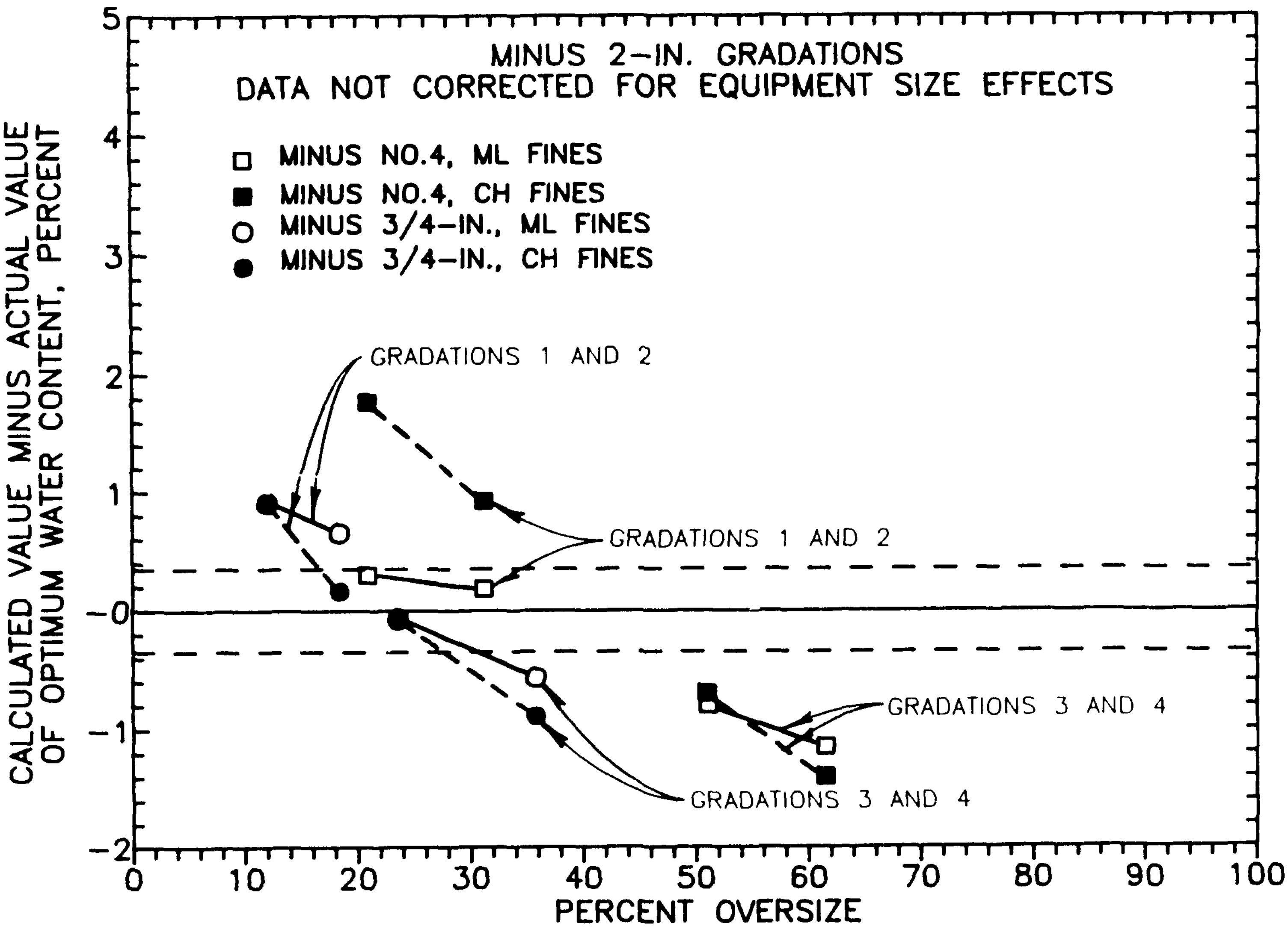


Figure 179. Predictions of optimum water contents of minus 2-in. gradations from those of minus 3/4-in. and No.4 fractions versus percent oversize, data not corrected for equipment size effects

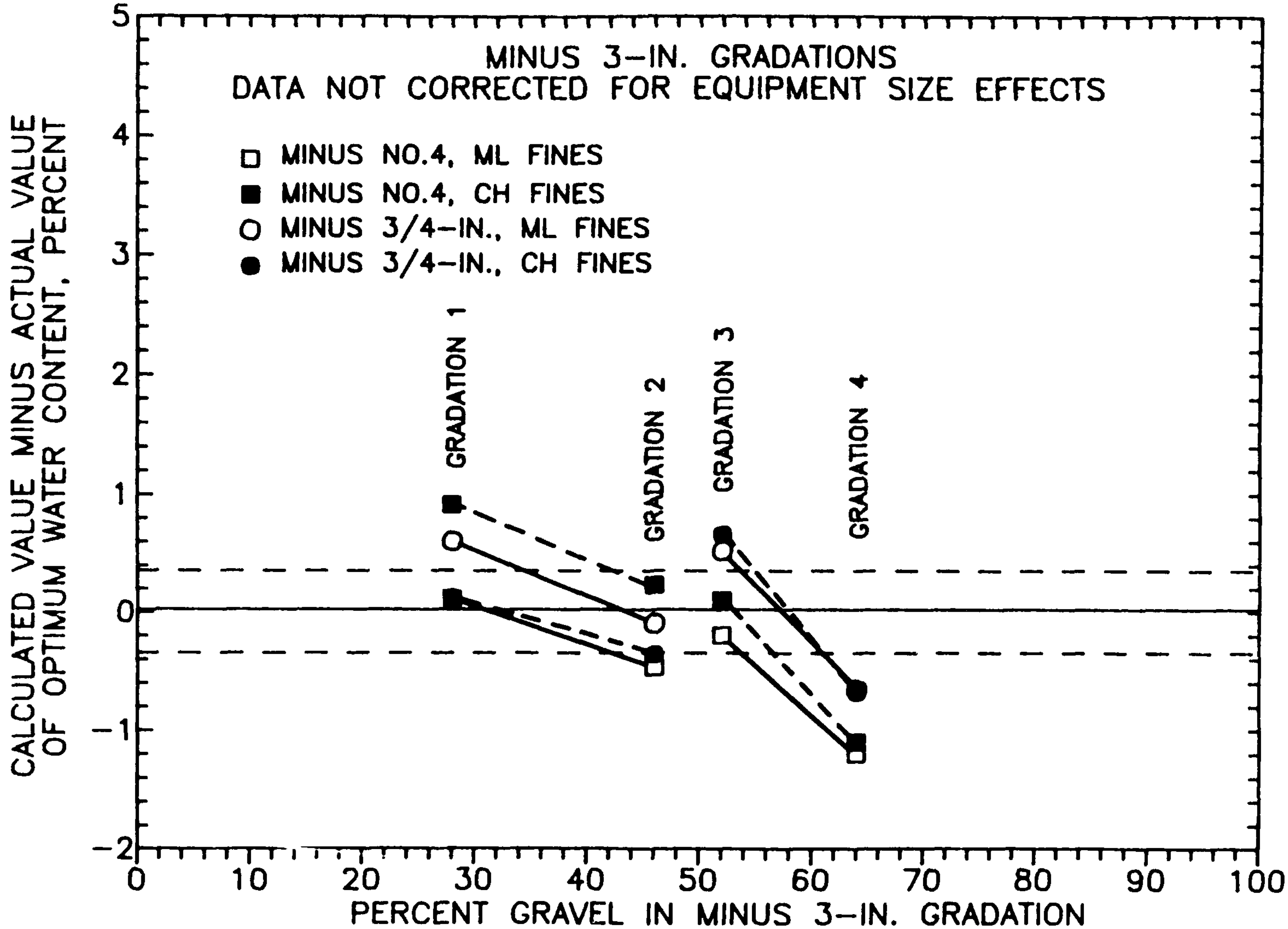


Figure 180. Predictions of optimum water contents of minus 3-in. gradations versus percent gravel in parent gradation, data not corrected for equipment size effects

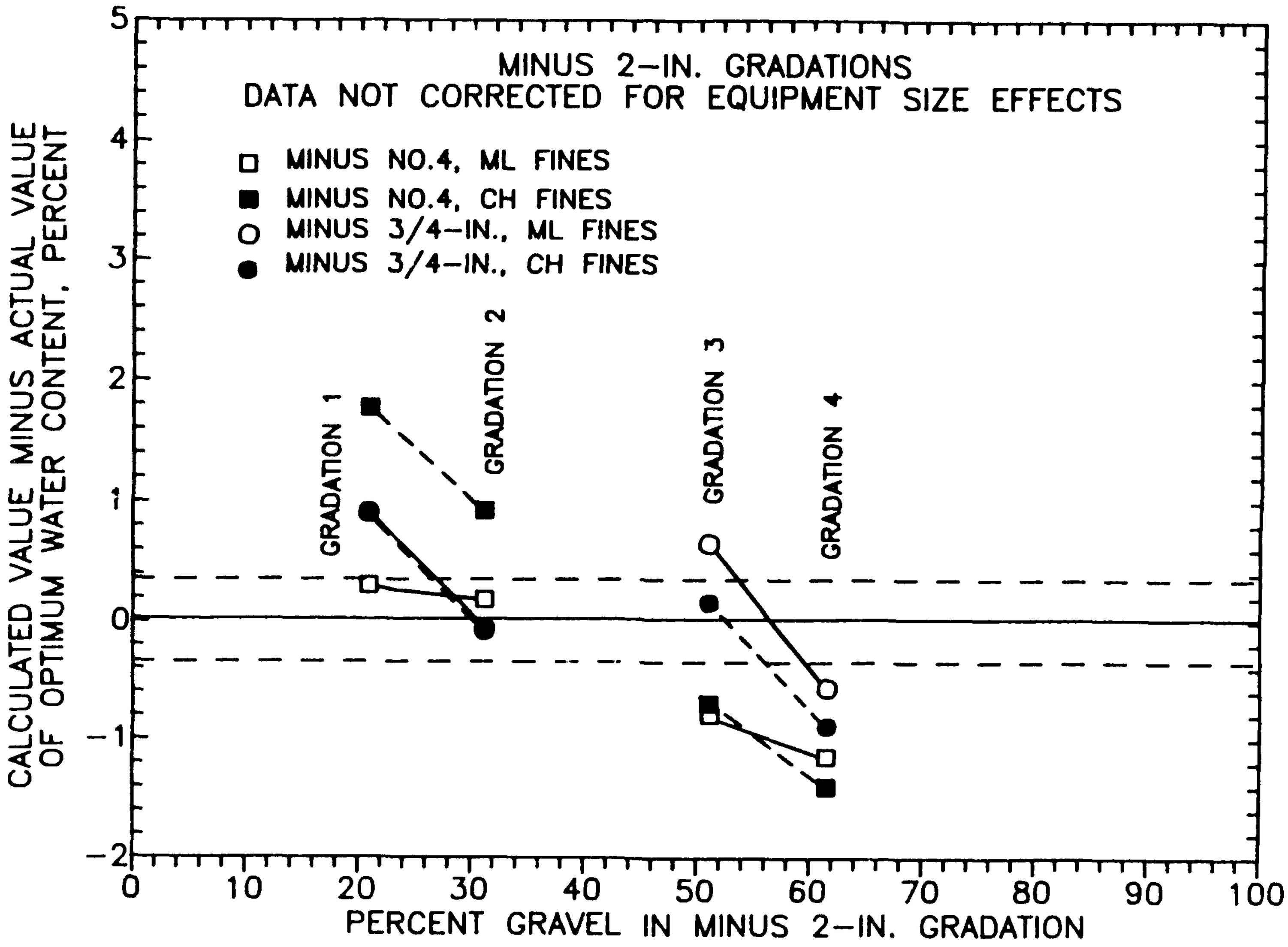


Figure 181. Predictions of optimum water contents of minus 2-in. gradations versus percent gravel in parent gradation, data not corrected for equipment size effects

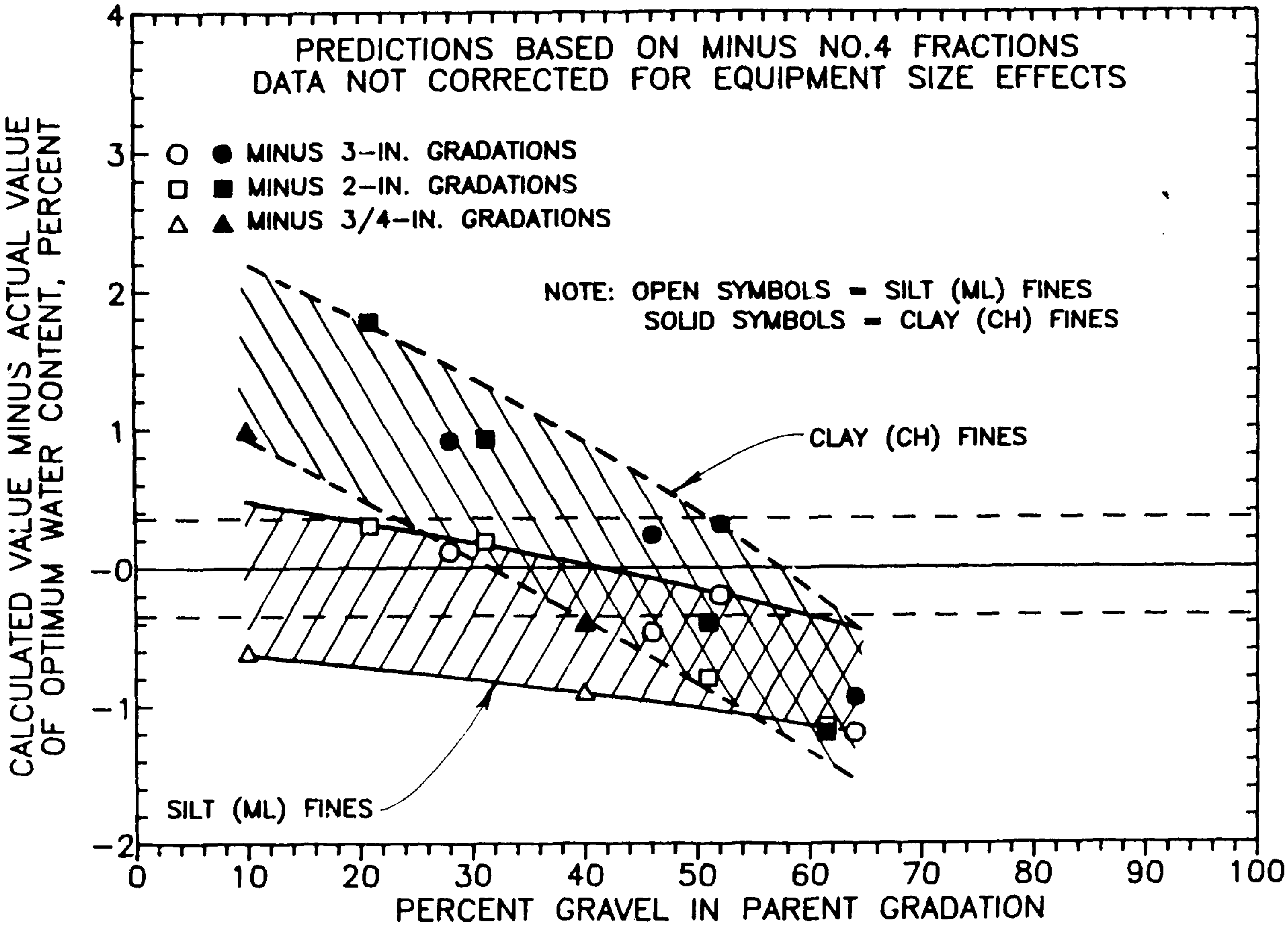


Figure 182. Summary plot for predictions of optimum water contents from those of minus No.4 fractions versus percent gravel in the parent gradation, data not corrected for equipment size effects

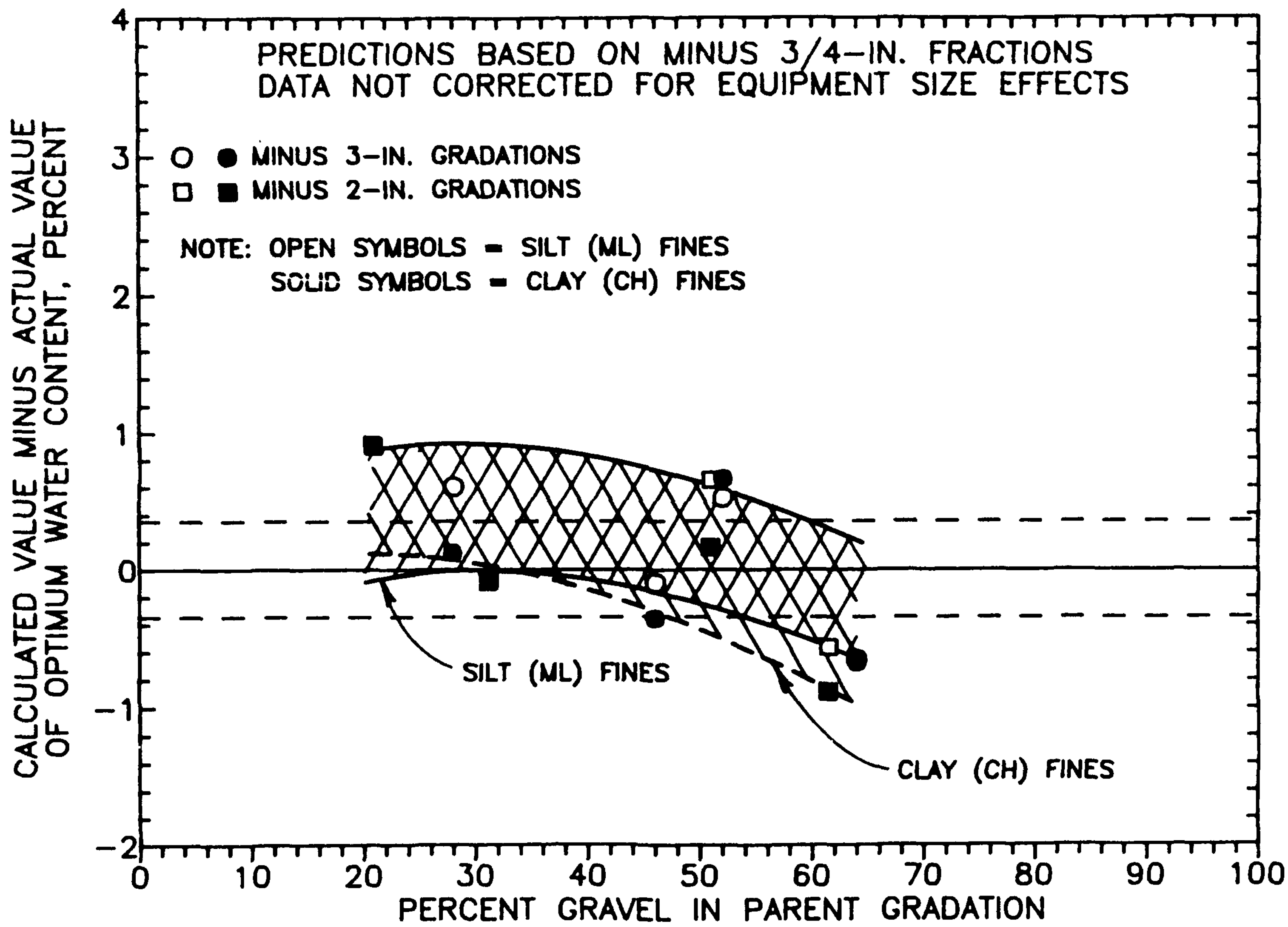


Figure 183. Summary plot for prediction of optimum water contents from those of minus 3/4-in. fractions versus percent gravel in the parent gradation, data not corrected for equipment size effects

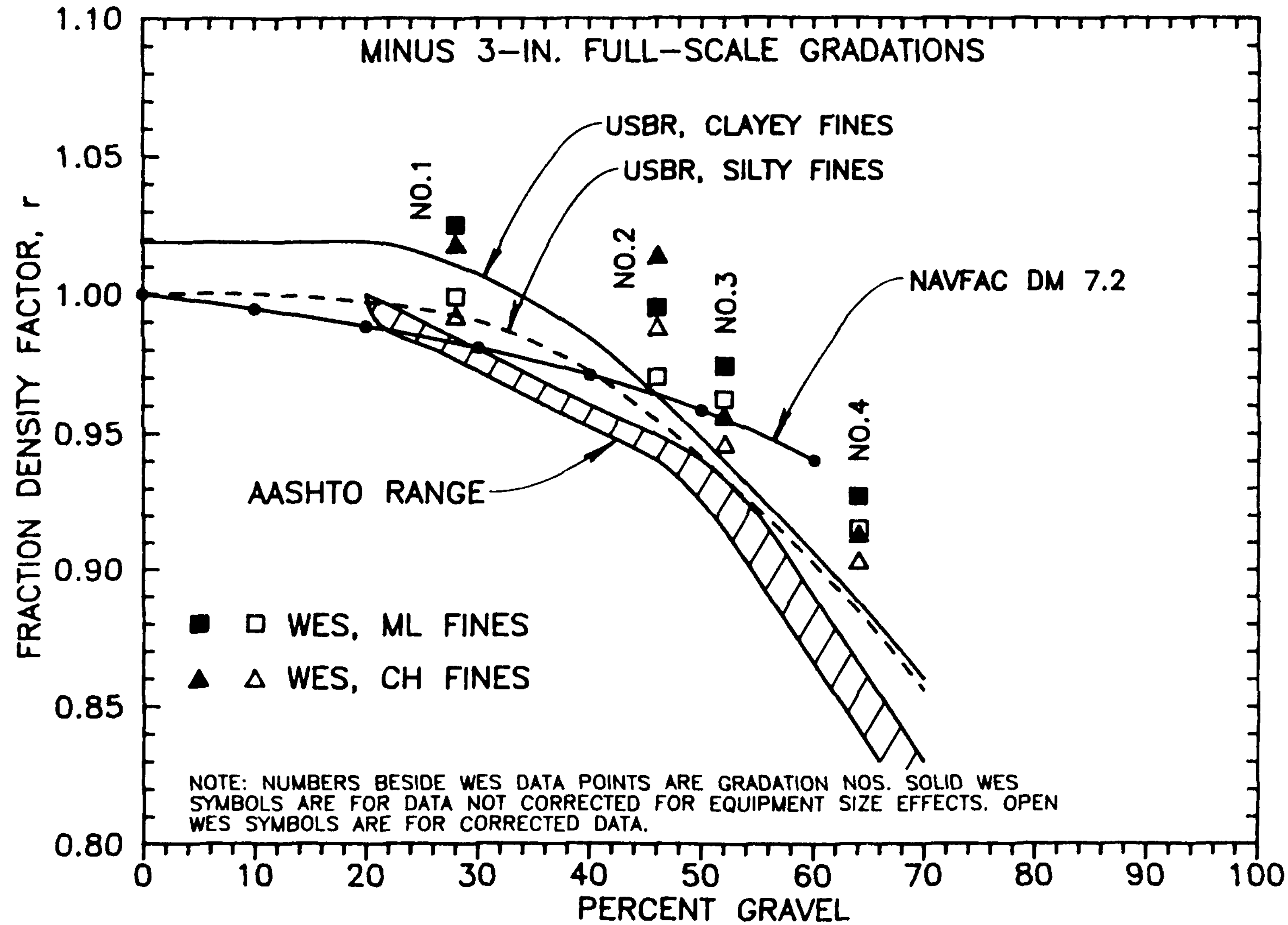


Figure 184. Comparison of WES, USBR, NAVFAC and AASHTO Fraction Density Factors for minus 3-in. gradations based on the minus No.4 fractions

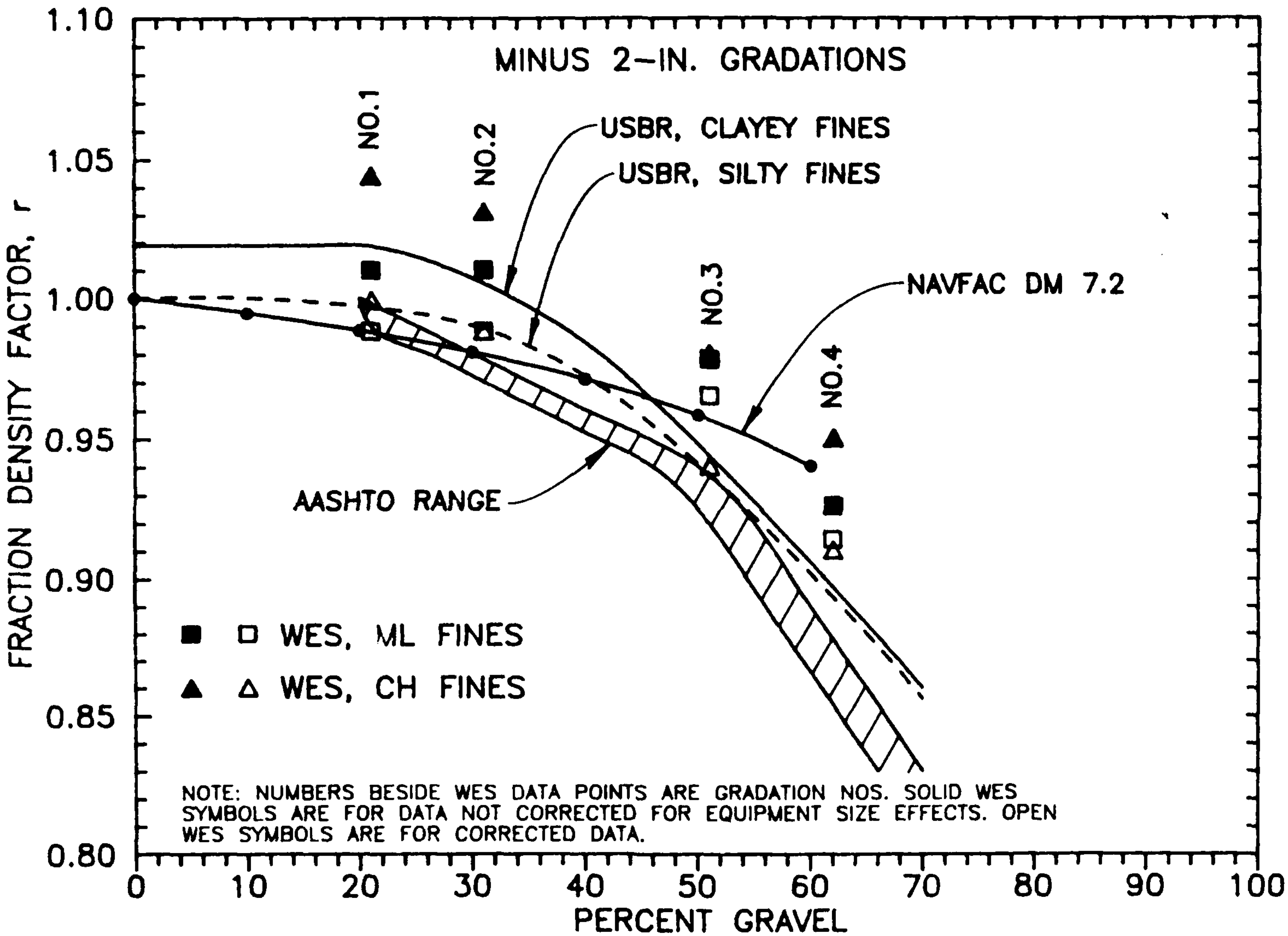


Figure 185. Comparison of WES, USBR, NAVFAC and AASHTO Fraction Density Factors for minus 2-in. gradations based on the minus No.4 fractions

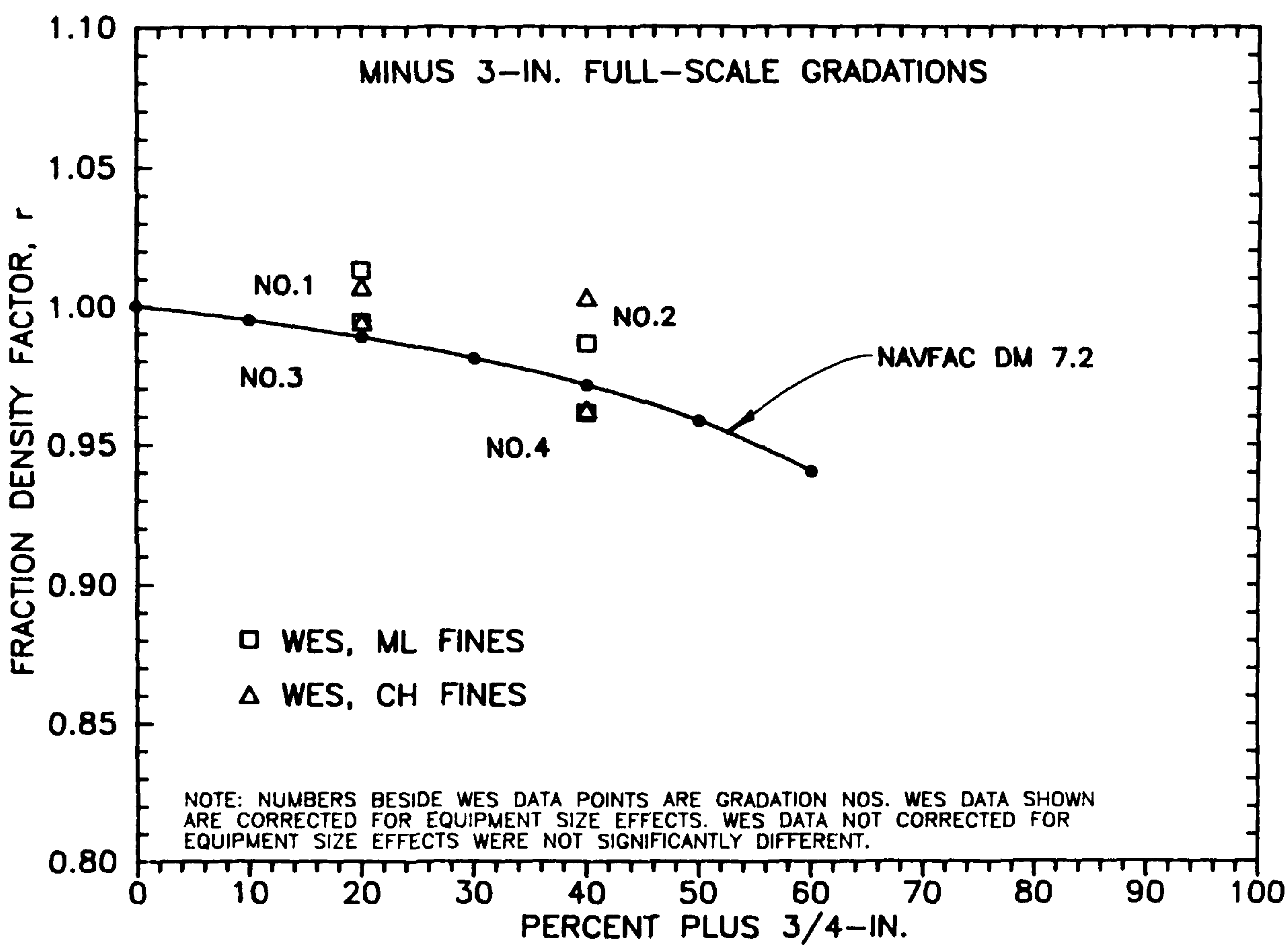


Figure 186. Comparison of WES, USBR, NAVFAC and AASHTO Fraction Density Factors for minus 3-in. gradations. WES factors based on the minus 3/4-in. fractions.

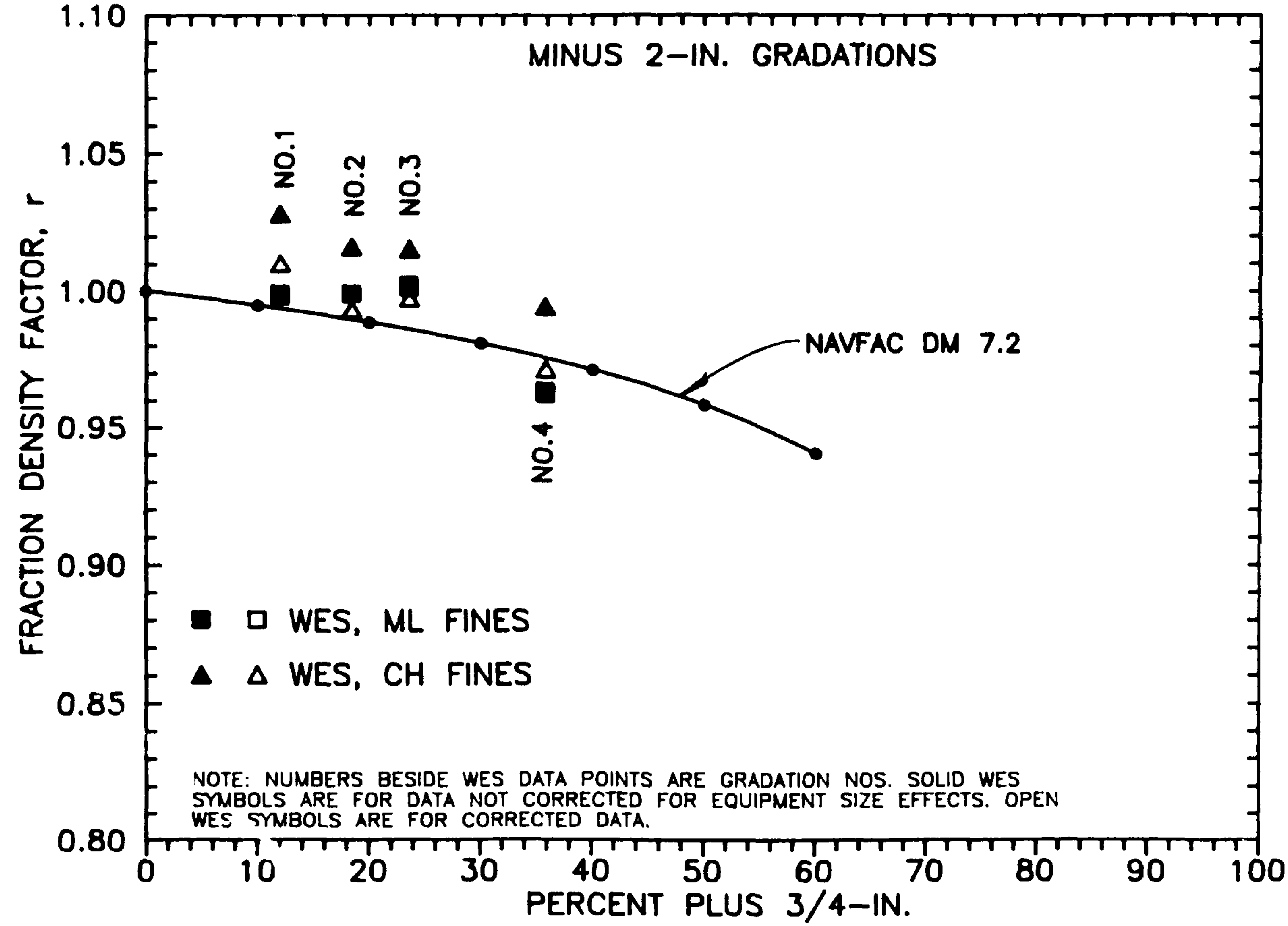


Figure 187. Comparison of WES, USBR, NAVFAC and AASHTO Fraction Density Factors for minus 2-in. gradations. WES factors based on the minus 3/4-in. fractions.

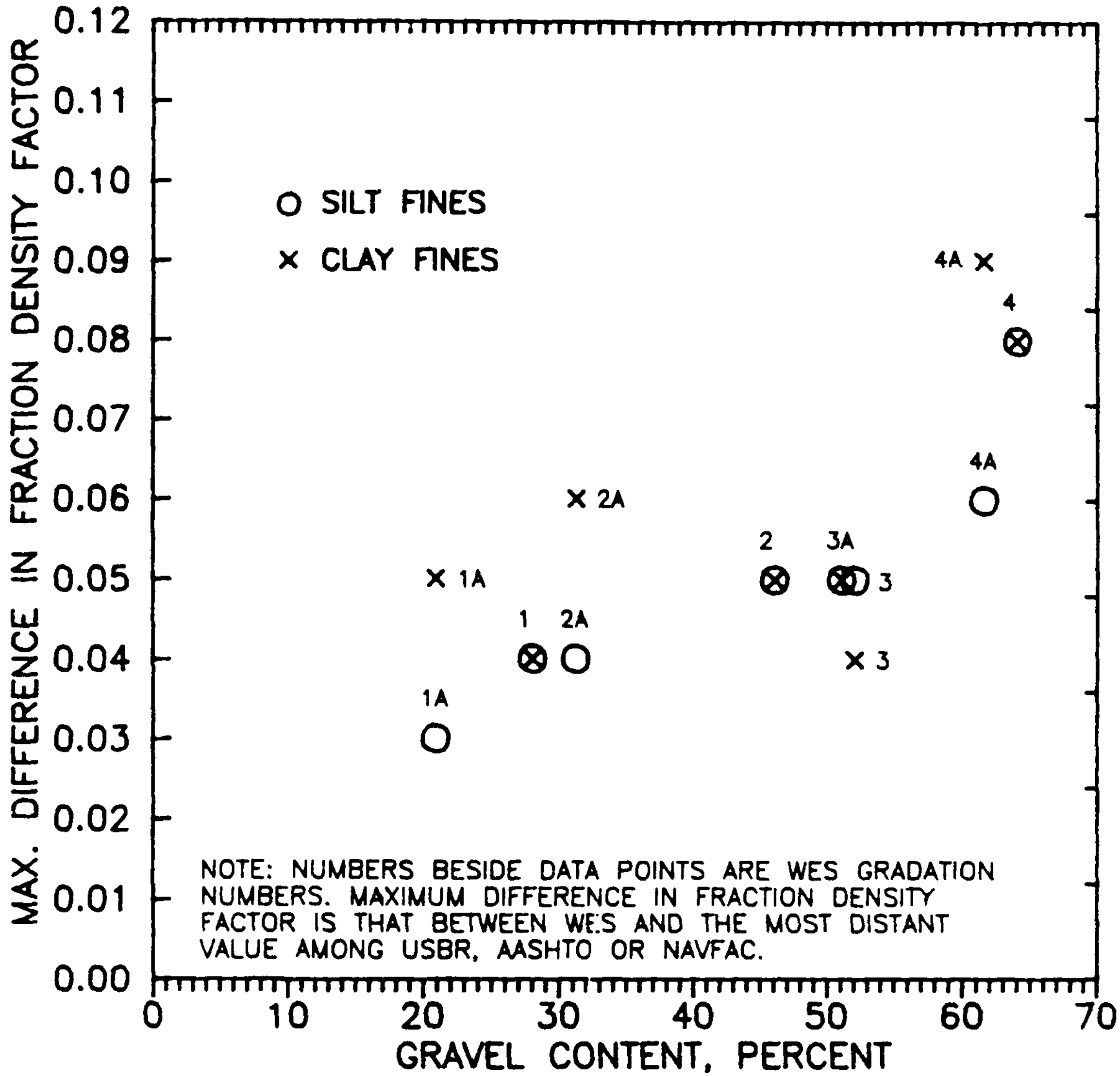


Figure 188. Maximum difference in Fraction Density Factors for individual gradations among WES, USBR, average AASHTO and NAVFAC

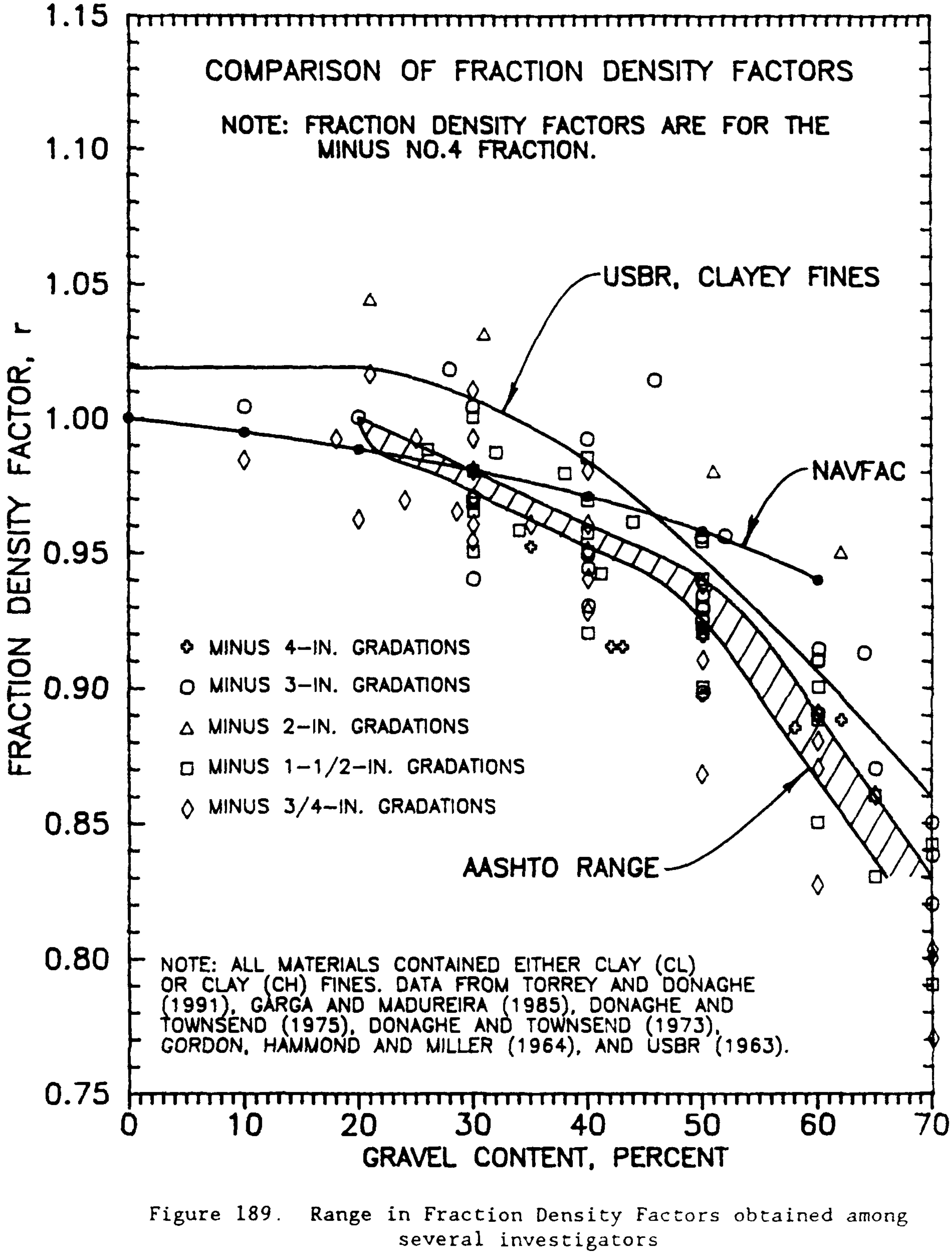


Figure 189. Range in Fraction Density Factors obtained among several investigators

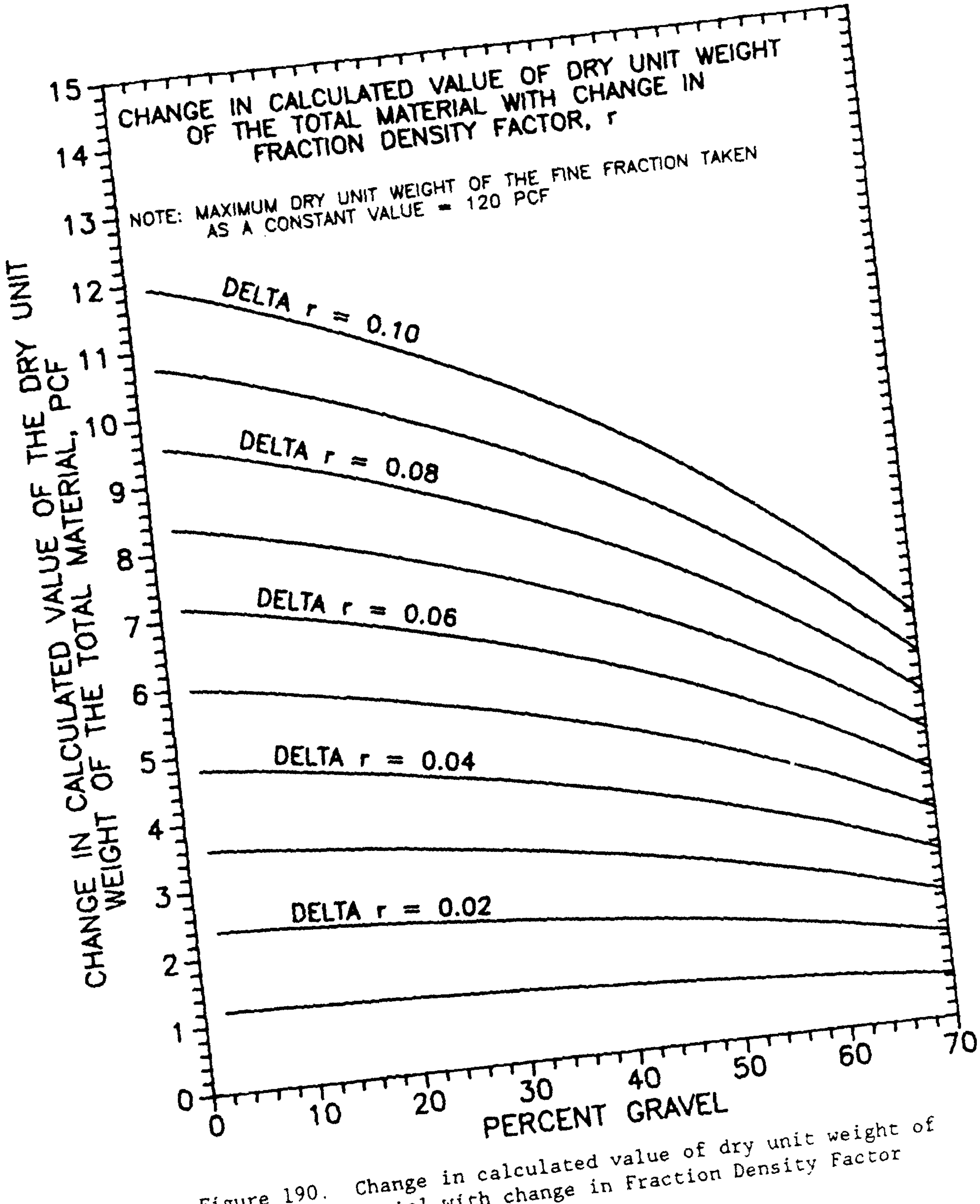


Figure 190. Change in calculated value of dry unit weight of the total material with change in Fraction Density Factor

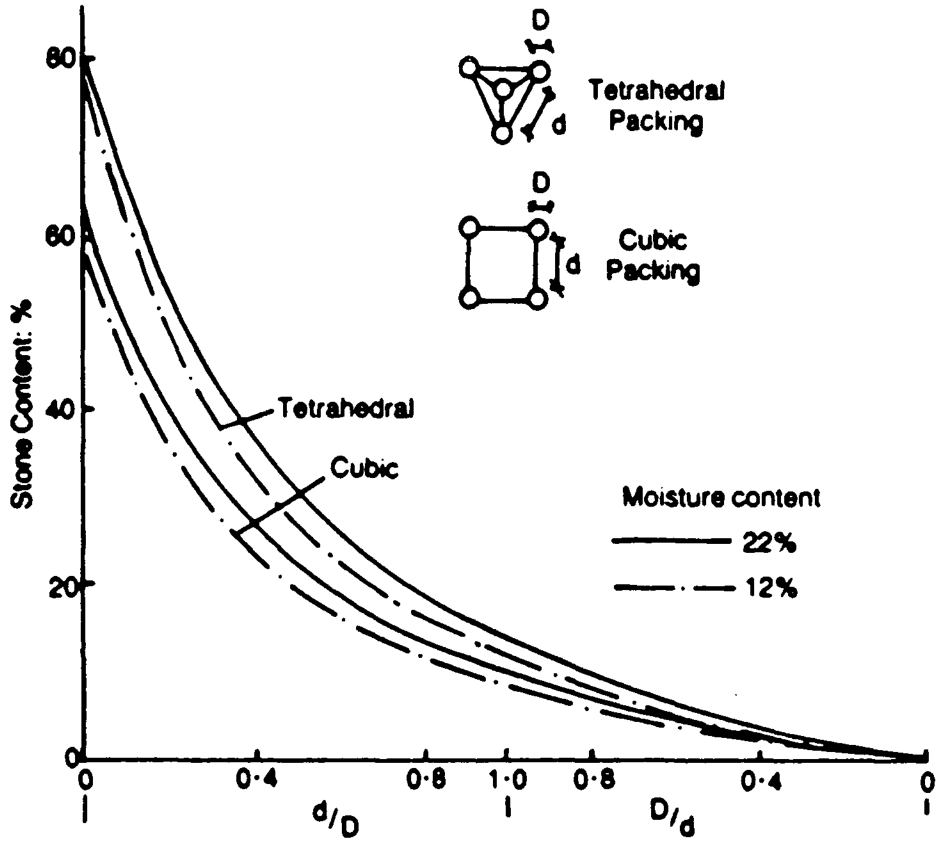


Figure 191. Spherical gravel particle separation

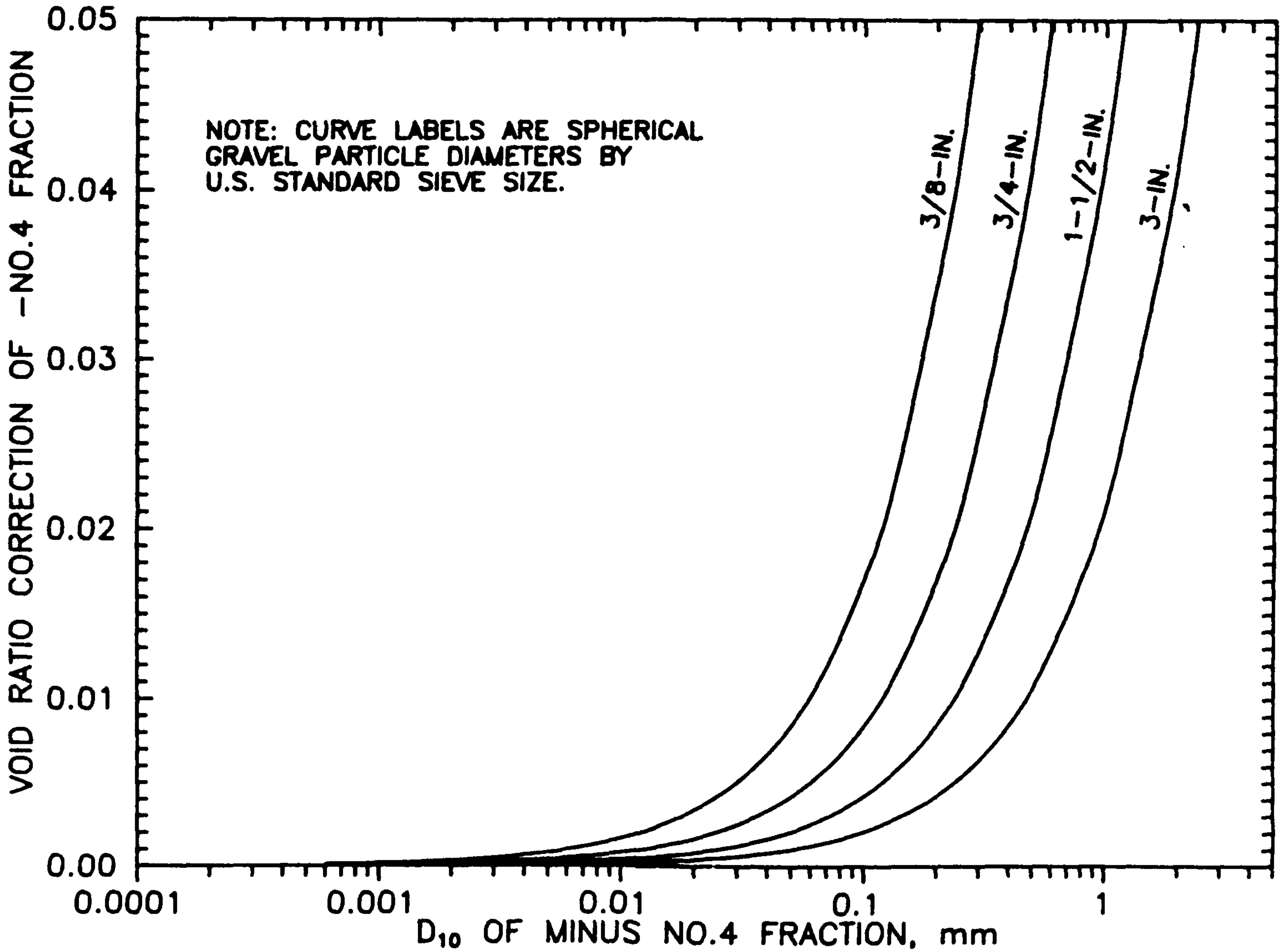


Figure 192. Correction to void ratio of the minus No.4 fraction due to the rigid boundary effect of spherical large particles

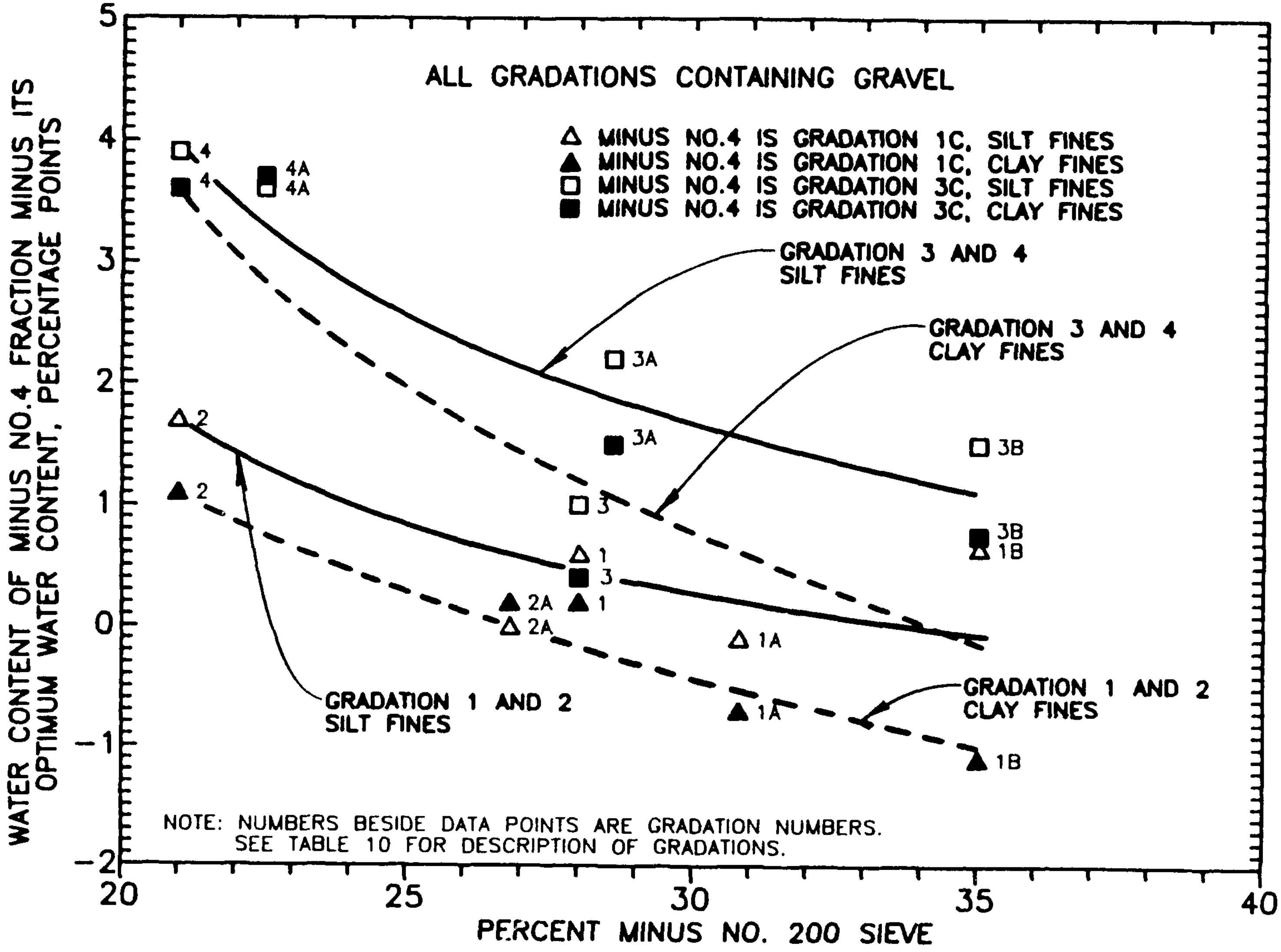


Figure 196. Water content of the minus No.4 fraction with respect to its optimum water content versus percent minus No. 200 in the total material

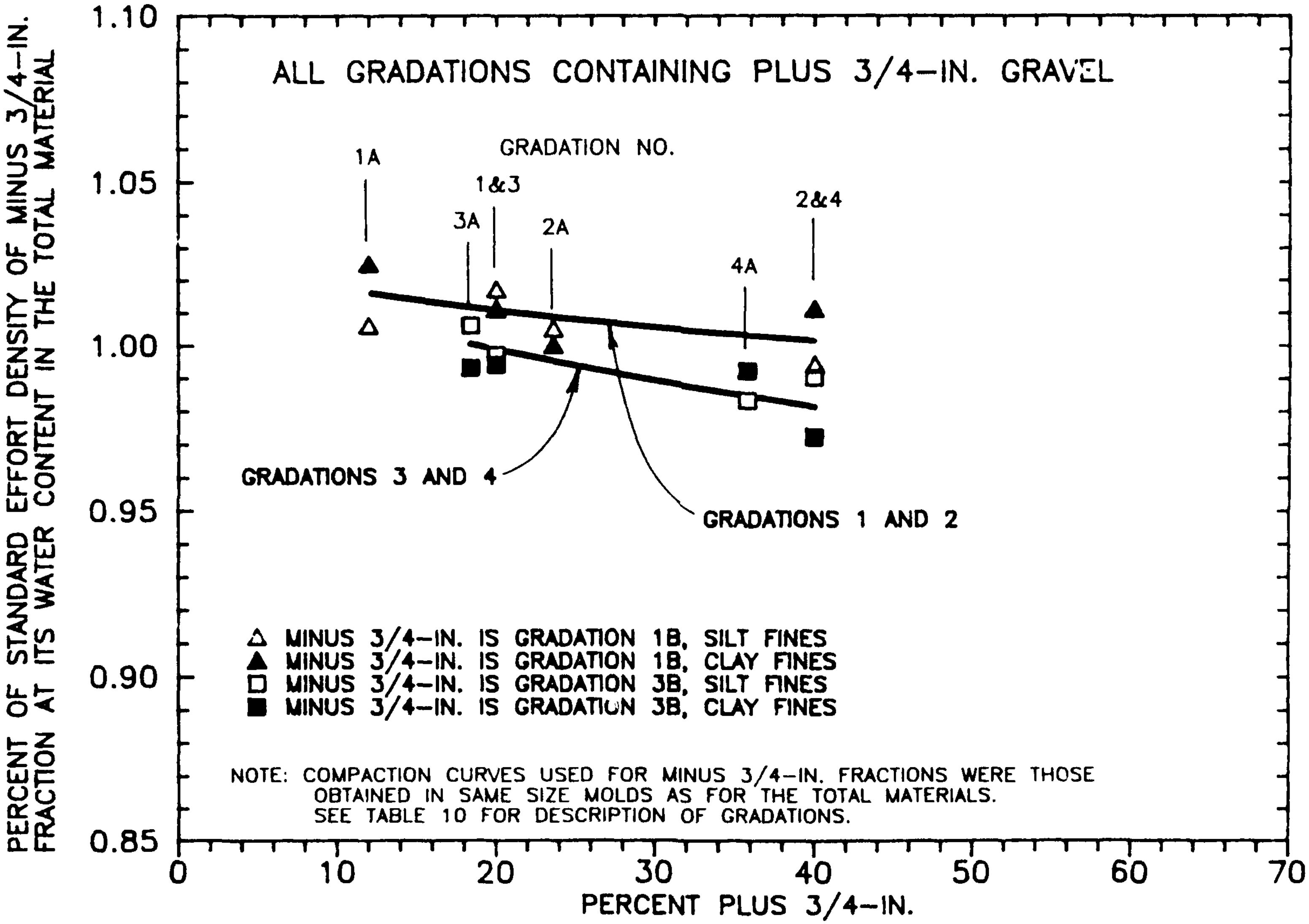


Figure 197. Percent of standard effort density of the minus 3/4-in. fraction at its water content in the total material versus percent plus 3/4-in. in the total material

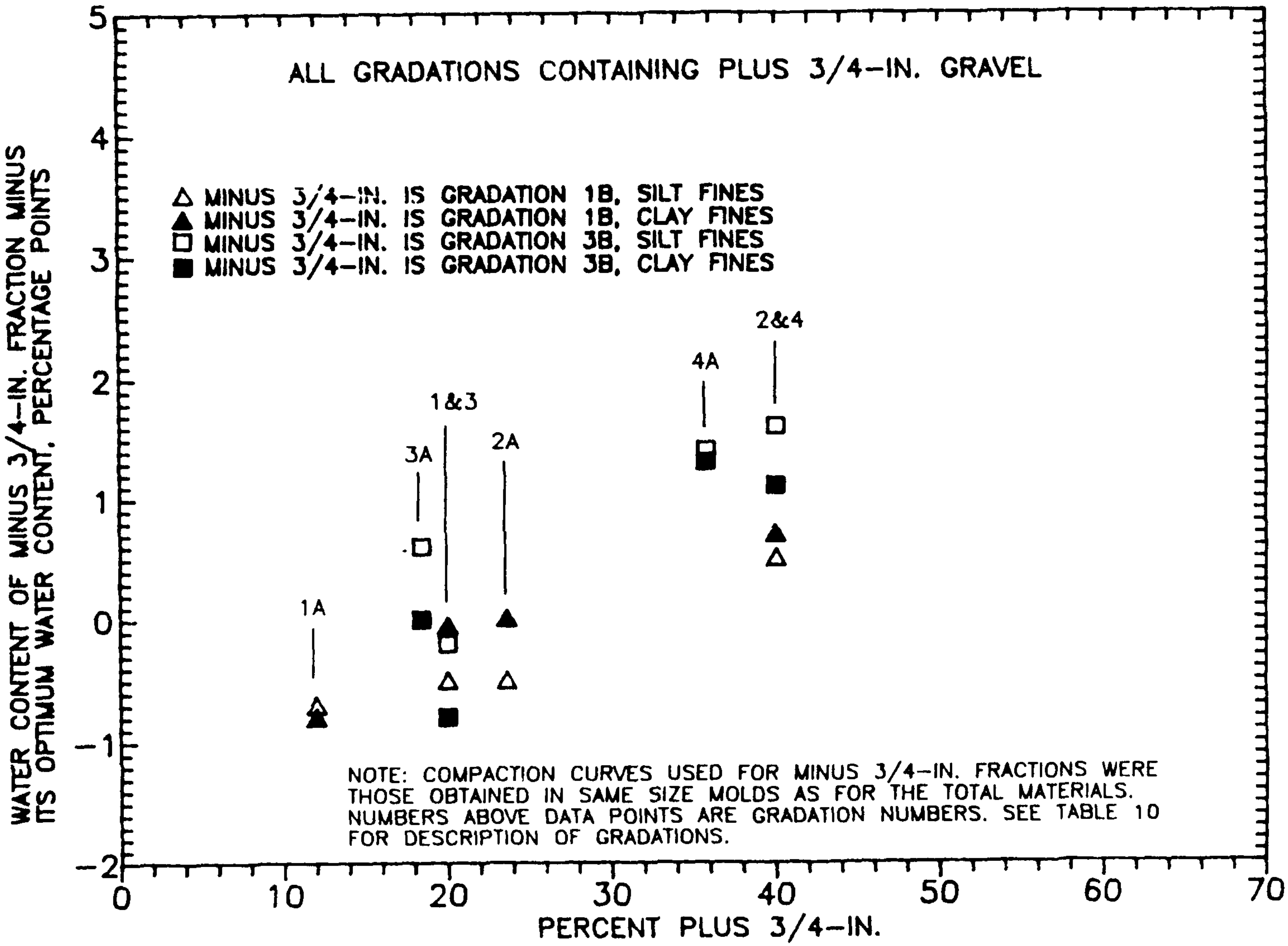


Figure 198. Water content of the minus 3/4-in. fraction with respect to its optimum water content versus percent plus 3/4-in. in the total material

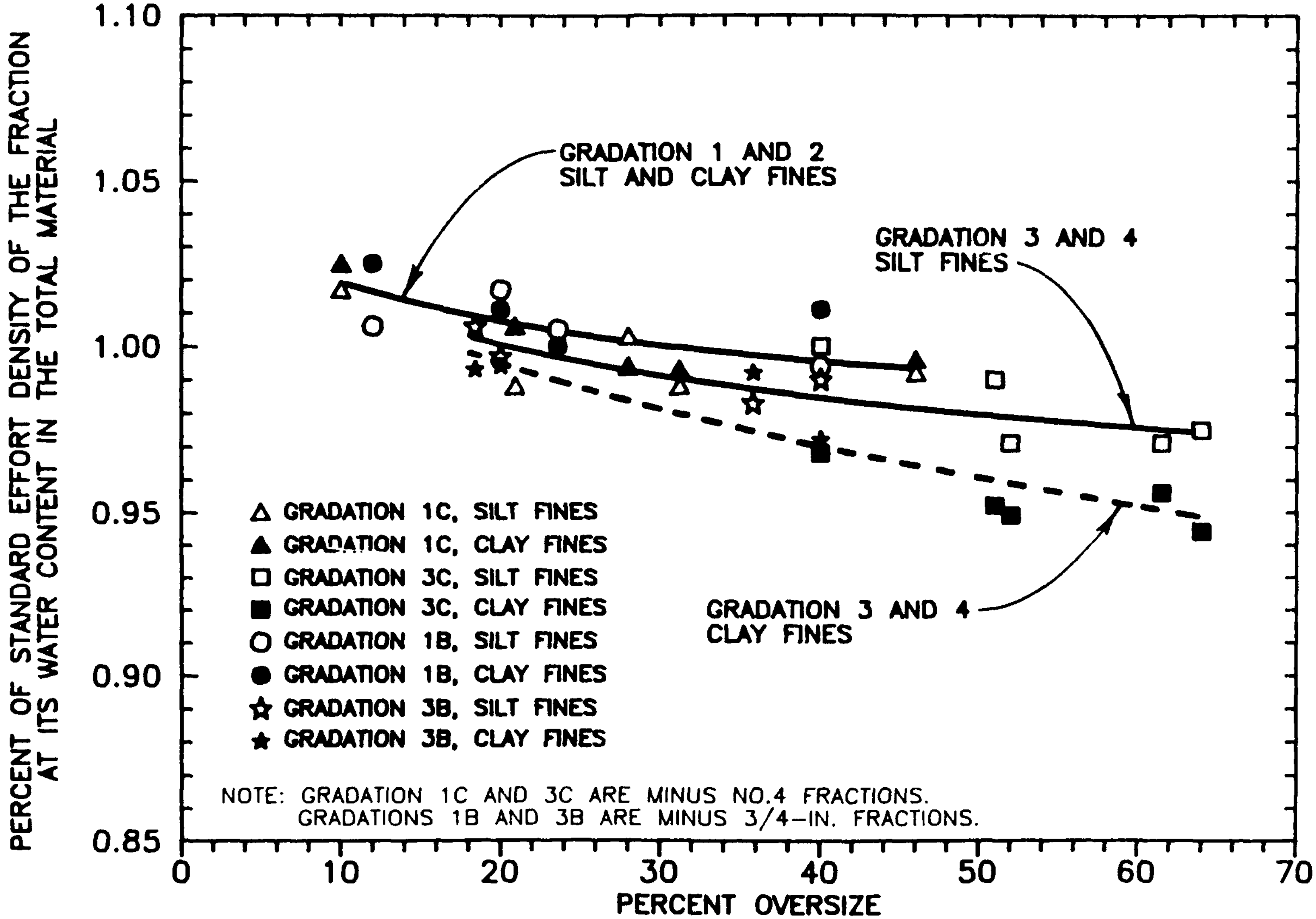


Figure 199. Percent of standard effort density of minus No.4 and minus 3/4-in. fractions at their water contents in the total material versus percent oversize

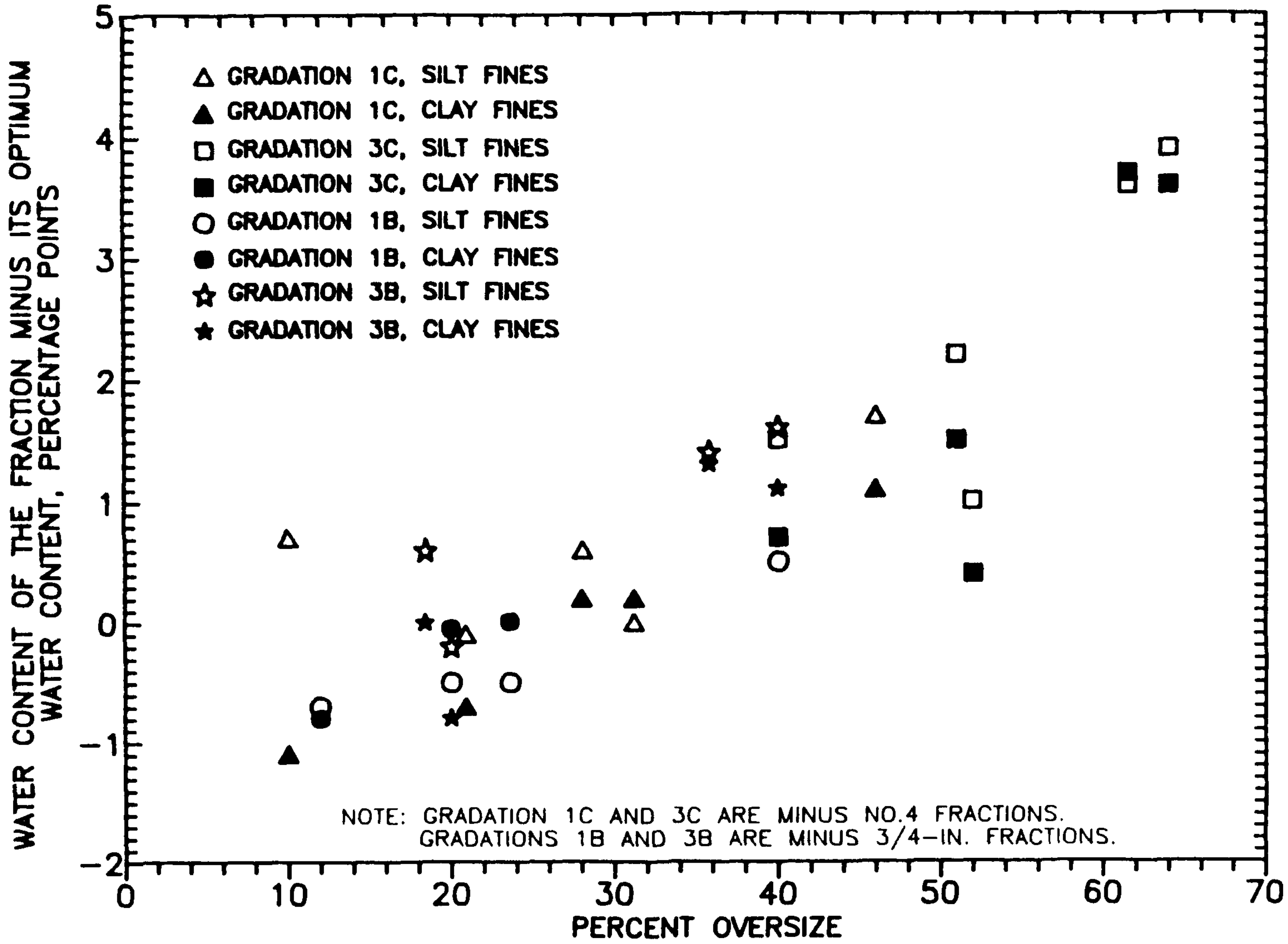


Figure 200. Water content of the minus No.4 and minus 3/4-in. fractions with respect to their optimum water contents versus percent oversize

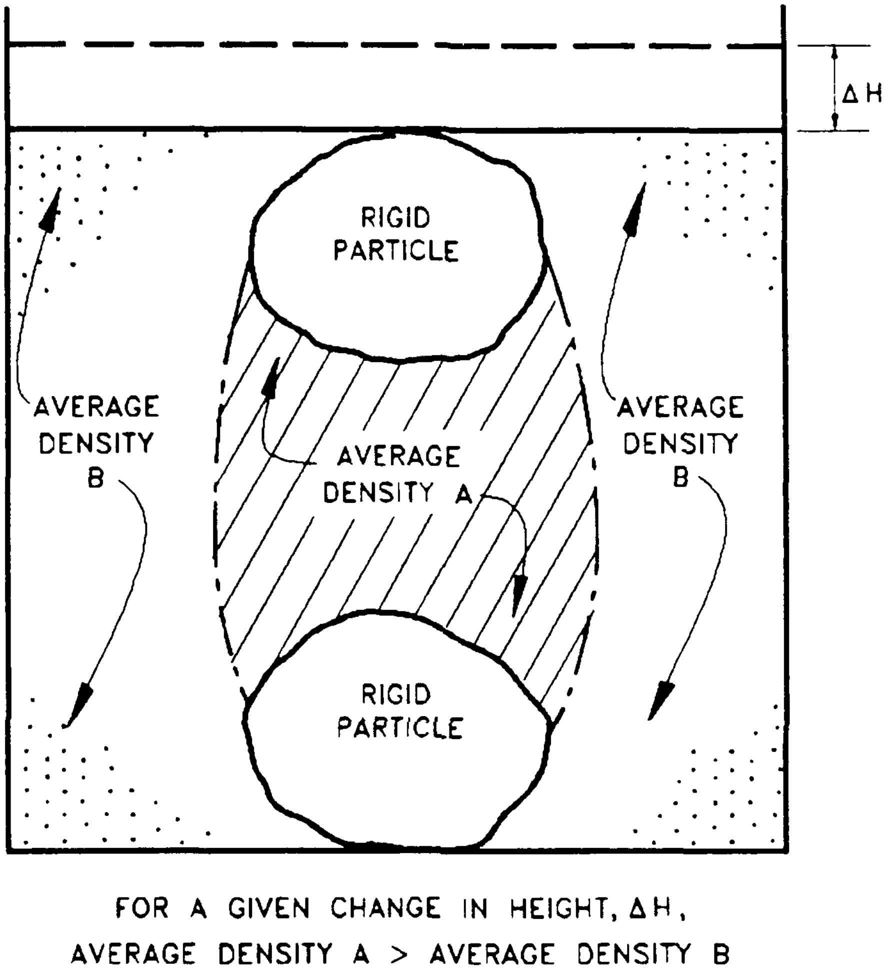


Figure 201. Increase in density of material between two rigid particle for a given uniform deformation of the specimen

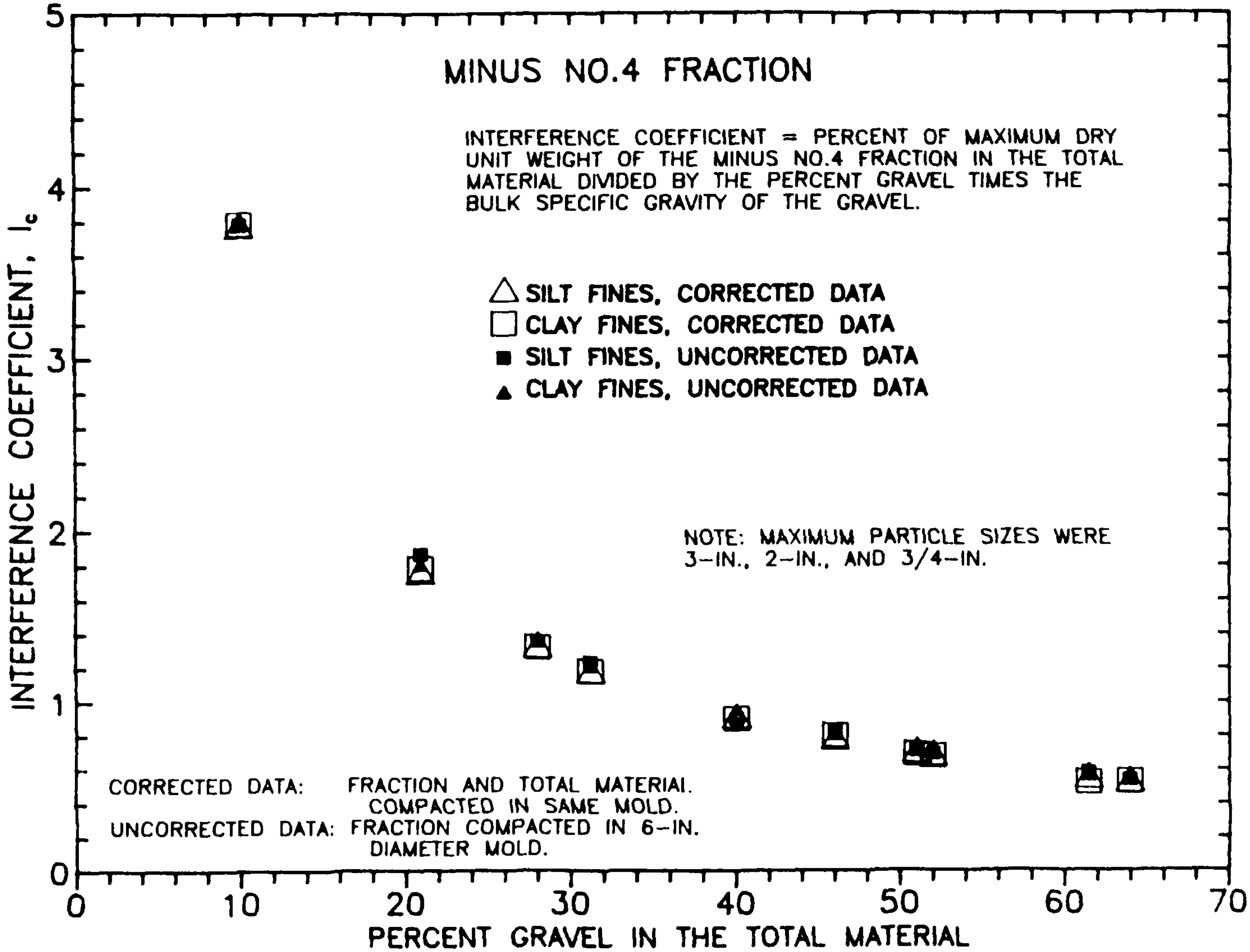


Figure 202. Density Interference Coefficient, I_c, based on the minus No.4 fraction versus gravel content for corrected and uncorrected compaction data obtained from this study

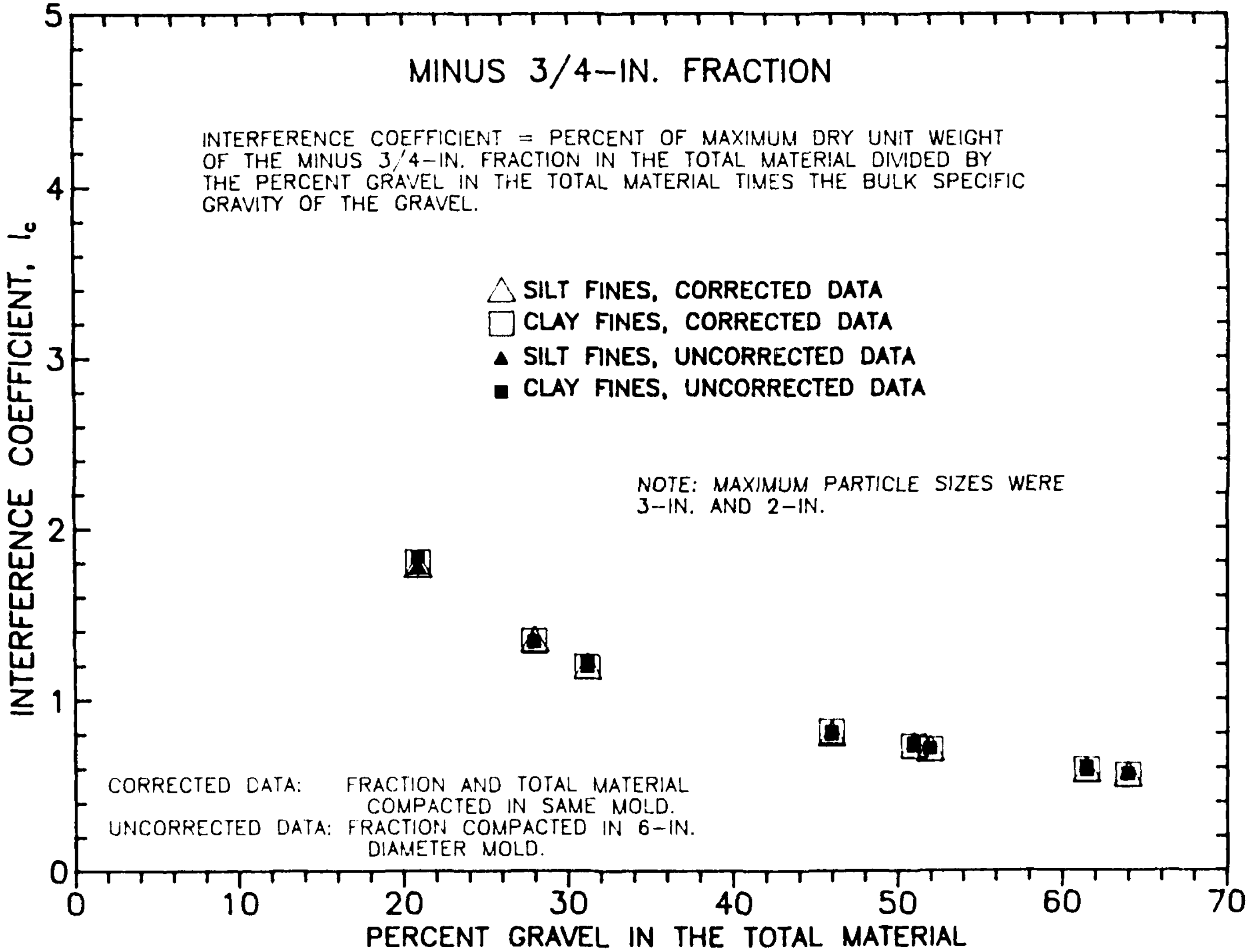


Figure 203. Density Interference Coefficient, I_c, based on minus 3/4-in. fraction versus gravel content in the total material for corrected and uncorrected compaction data from this study

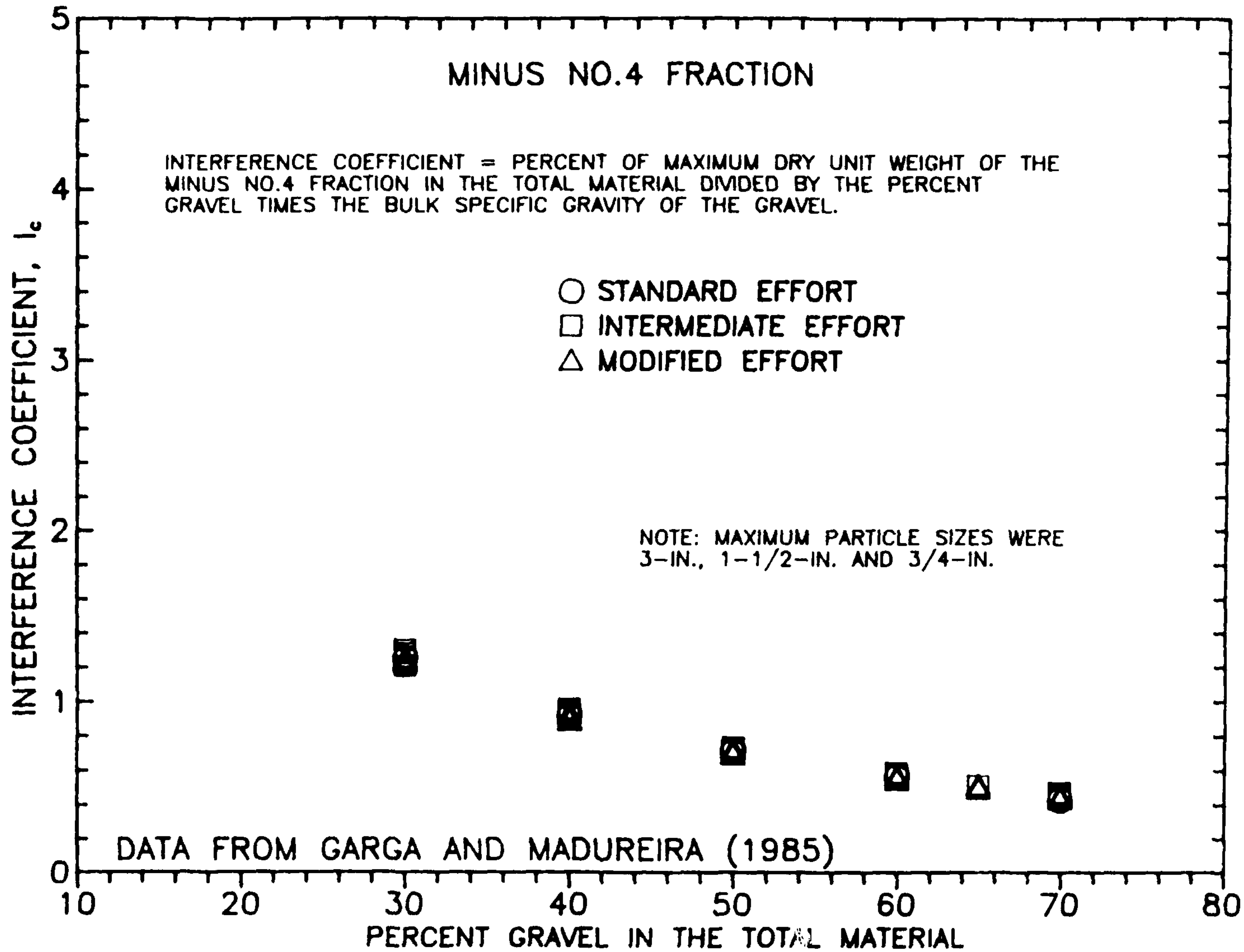


Figure 204. Density Interference Coefficient, I_c, based on the minus No.4 fraction versus gravel content for compaction data reported by Garga and Madureira (1985)

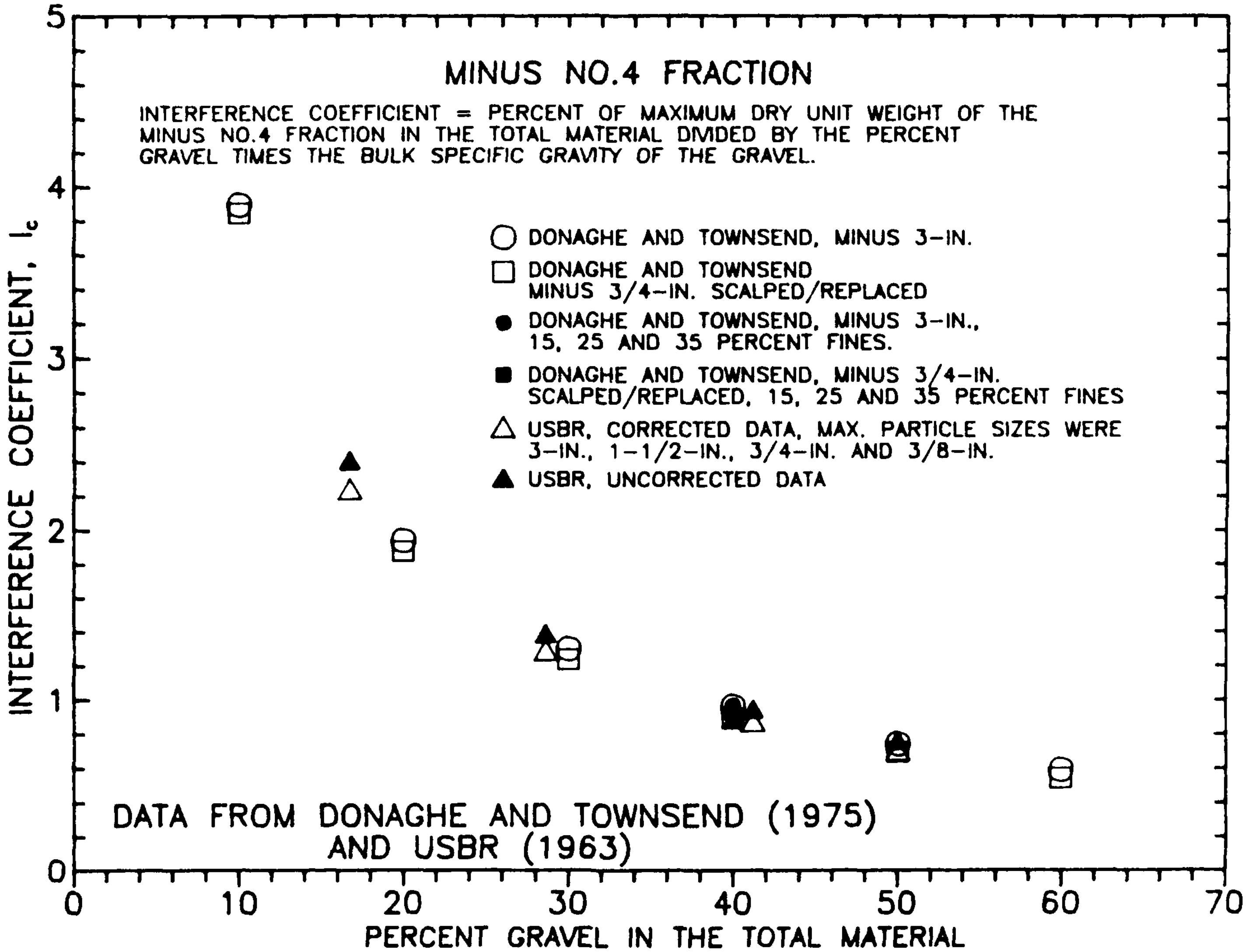


Figure 205. Density Interference Coefficient, I_c, based on the minus No.4 fraction versus gravel content for compaction data reported by Donaghe and Townsend (1975) and USBR (1963)

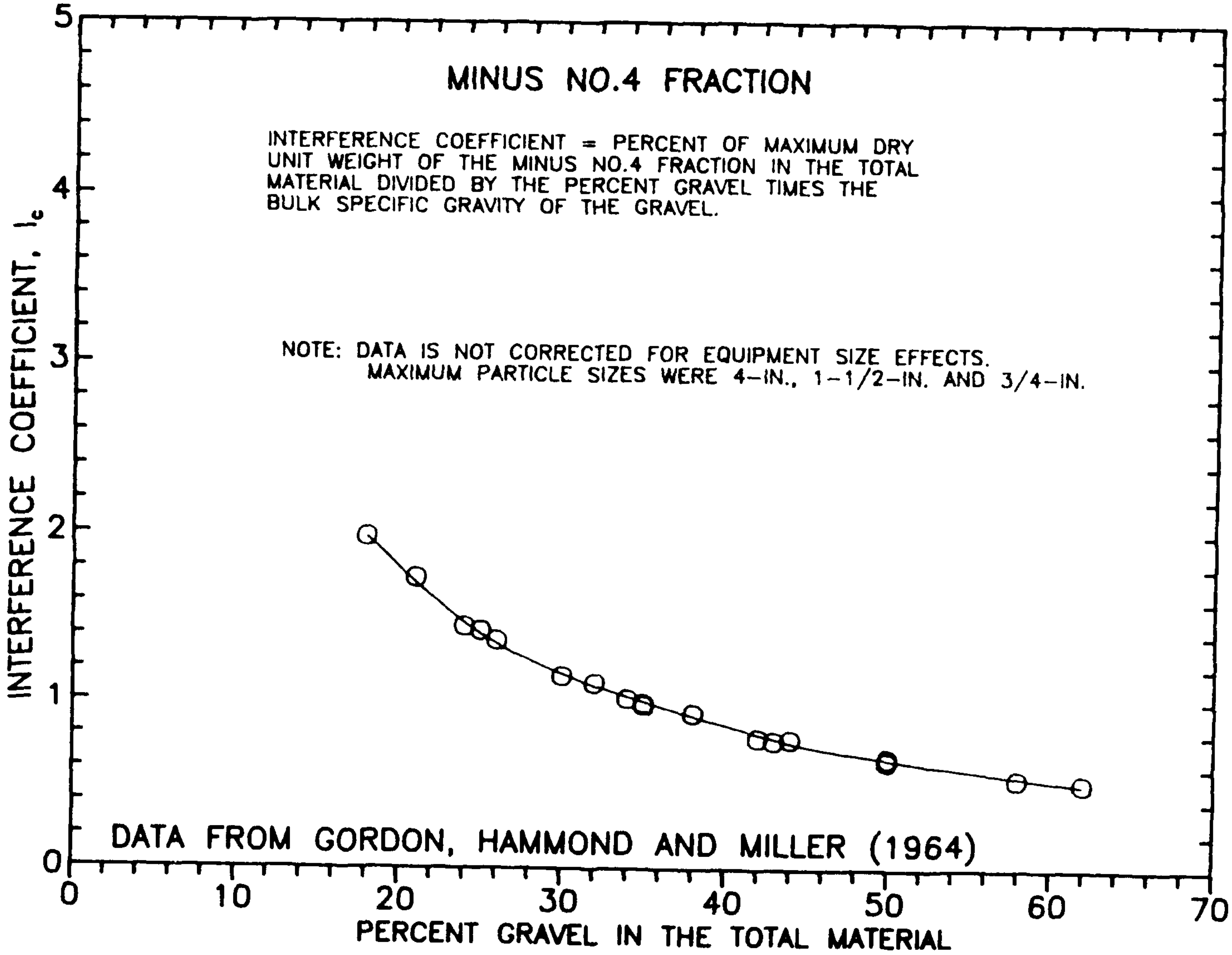


Figure 206. Density Interference Coefficient, I_c, based on the minus No.4 fraction versus gravel content for compaction data reported by Gordon, Hammond and Miller (1964)

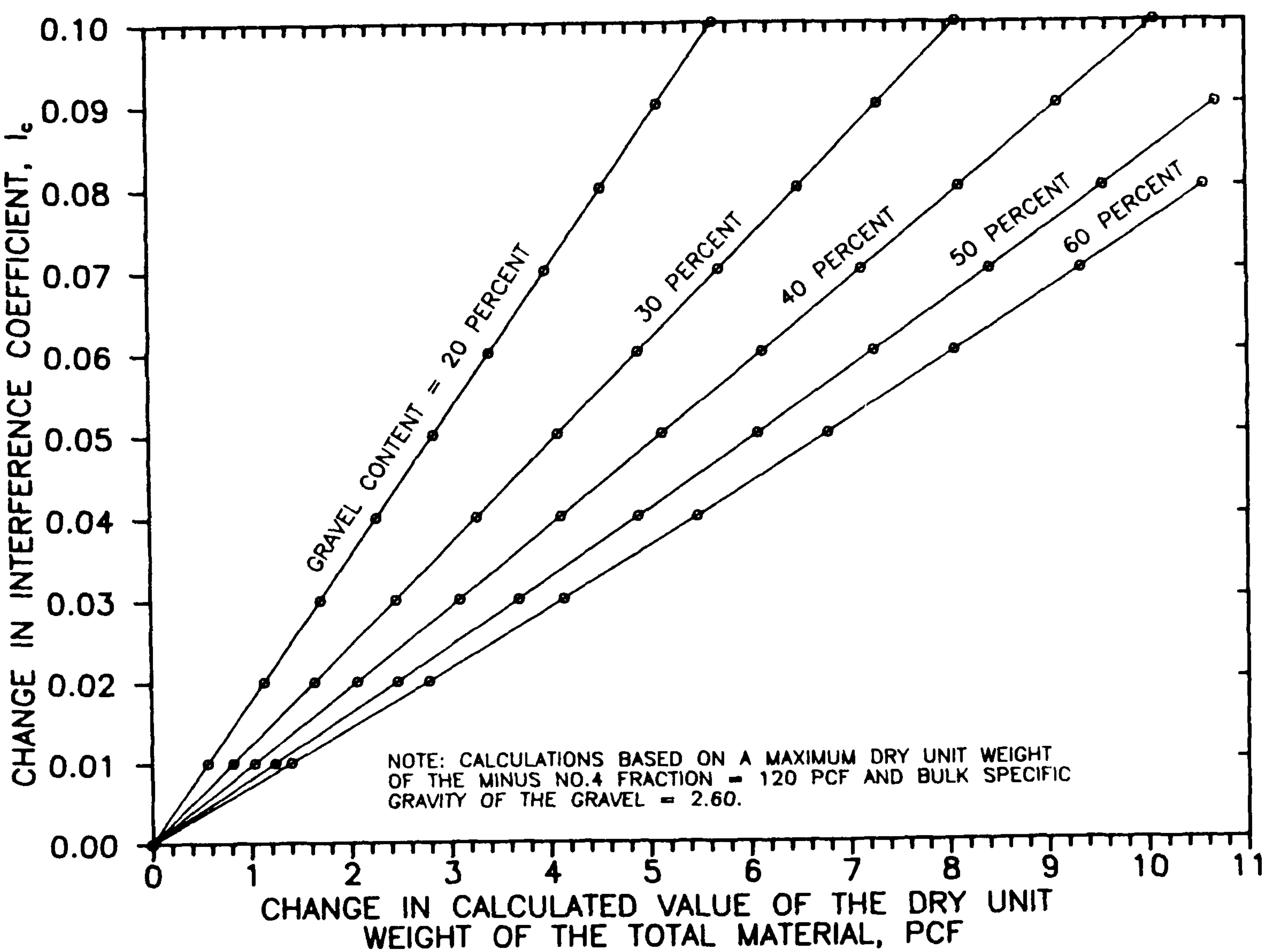


Figure 207. Change in calculated value of maximum dry unit weight of the total material with change in density Interference Coefficient

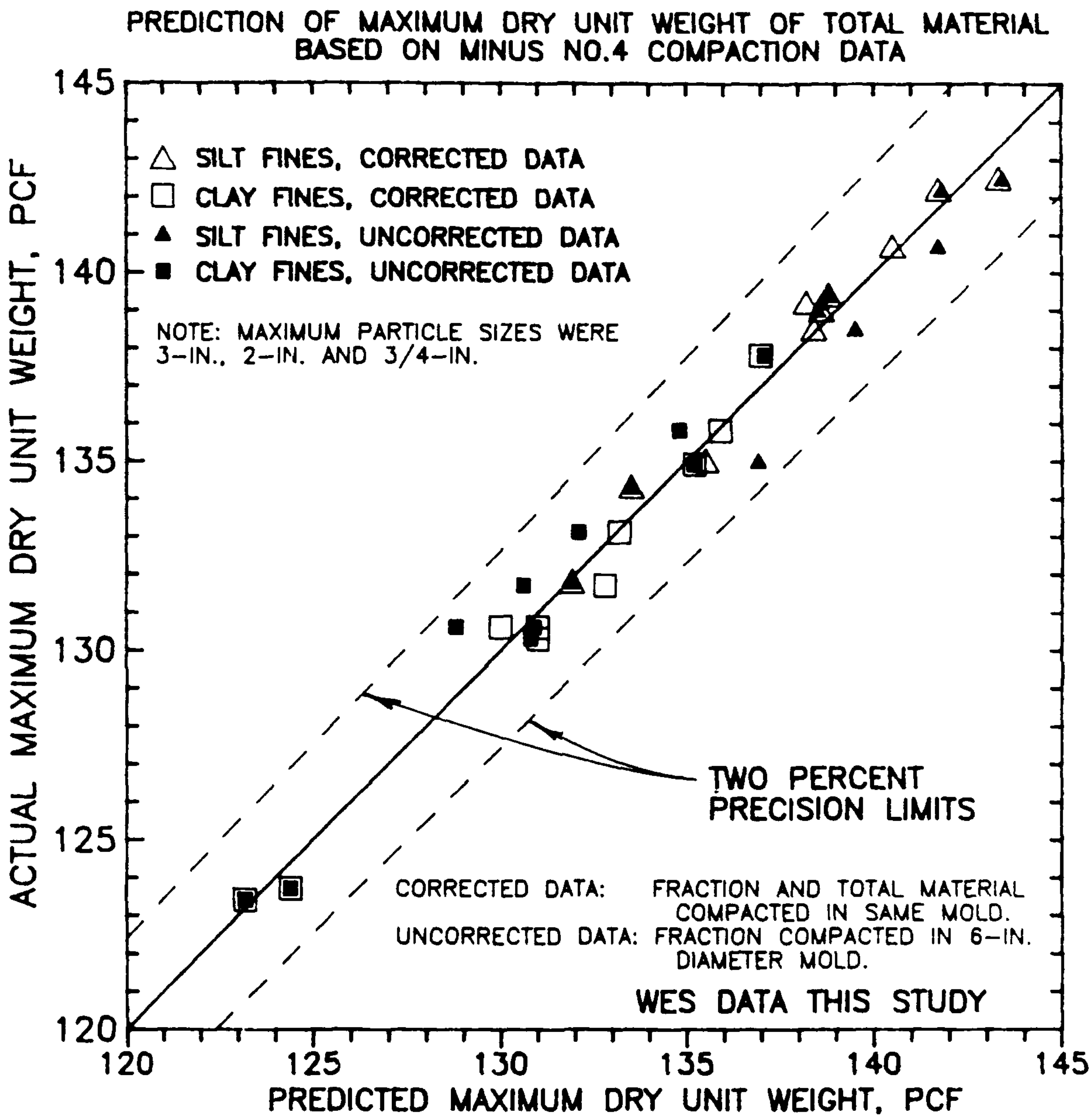


Figure 208. Prediction of maximum dry unit weight of the total material using estimated-fit density Interference Coefficient versus gravel content curves based on the minus No.4 fraction

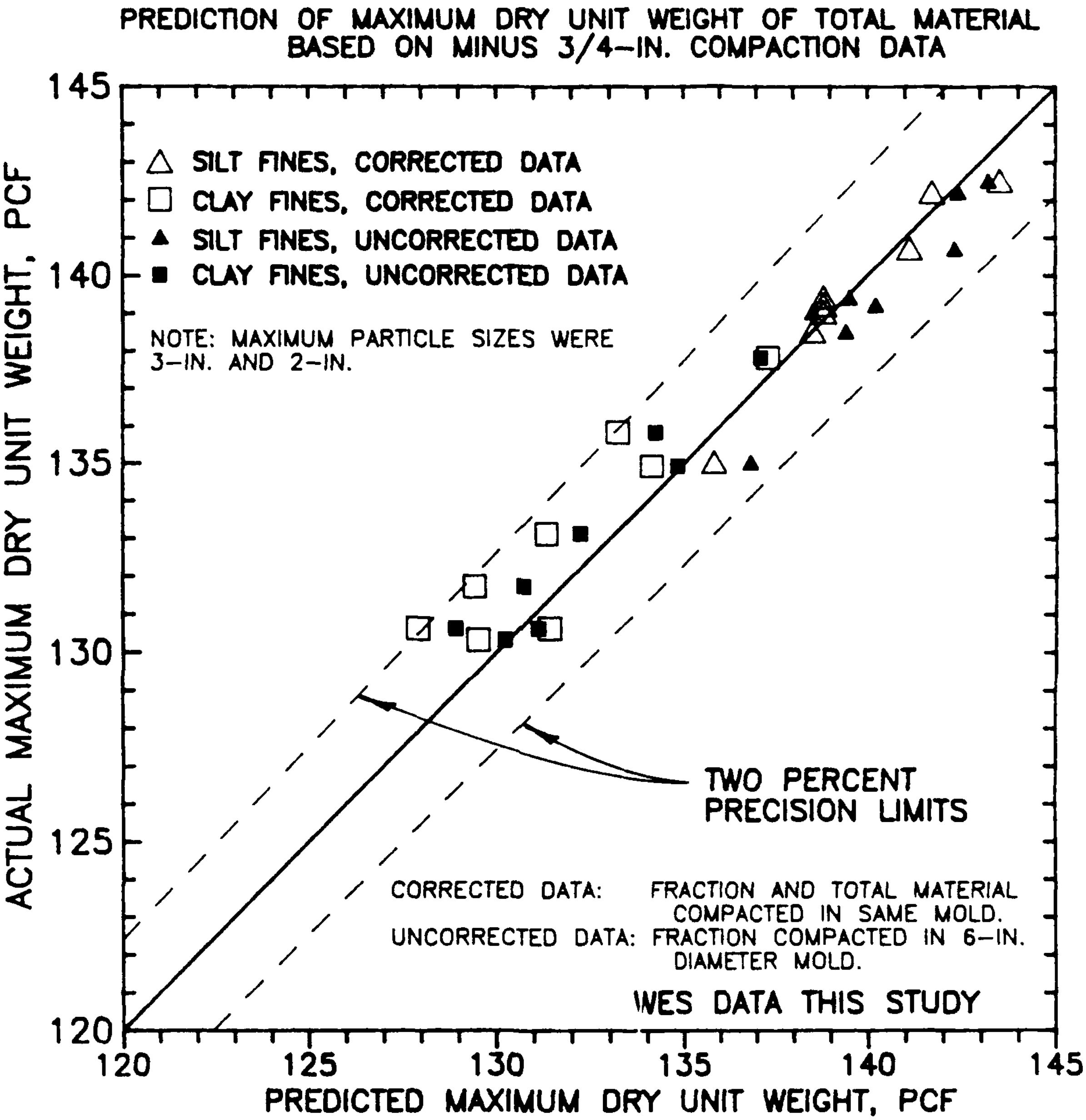


Figure 209. Prediction of maximum dry unit weight of the total material using estimated-fit density Interference Coefficient versus gravel content curves based on the minus 3/4-in. fraction

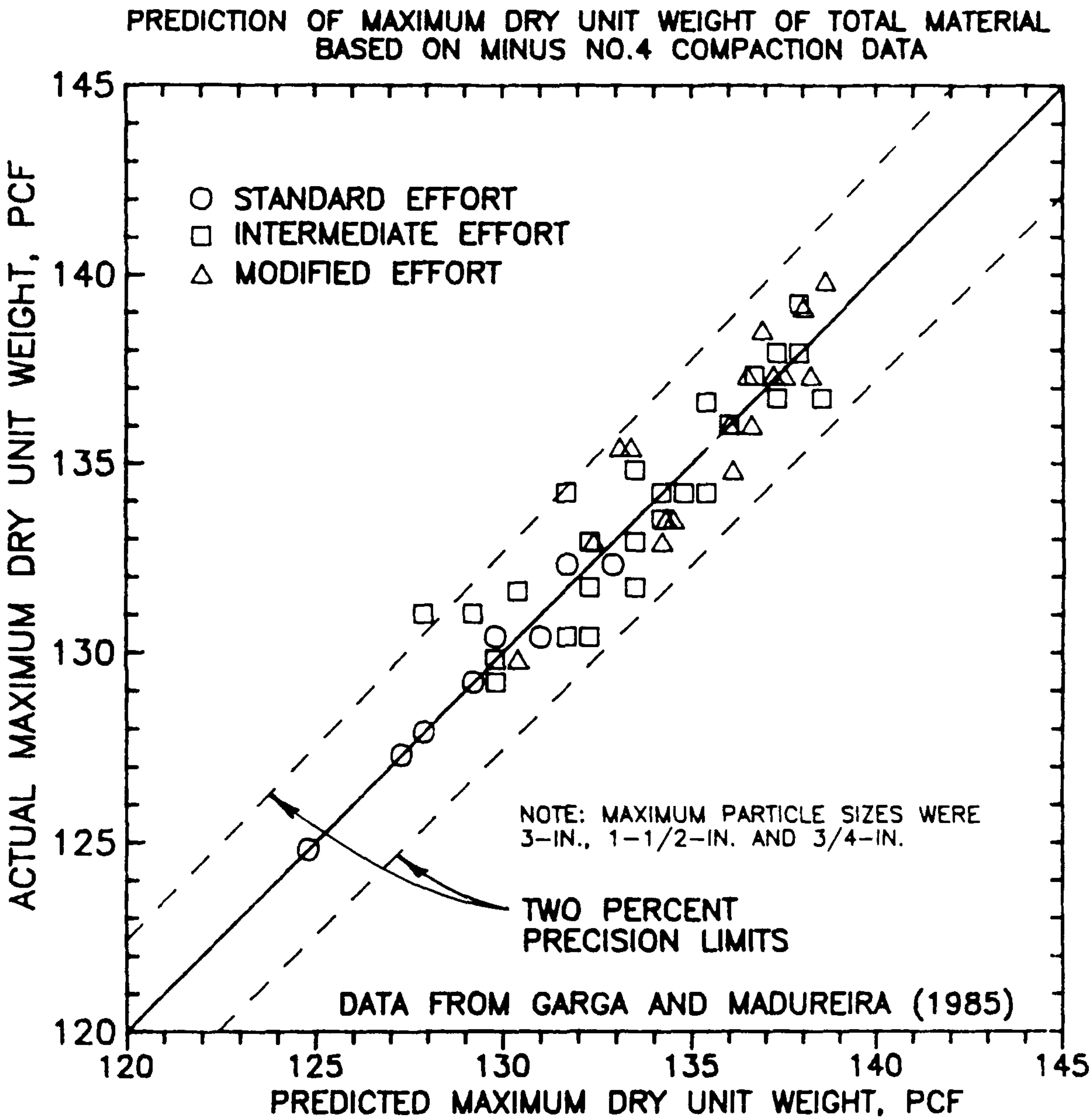


Figure 210. Prediction of maximum dry unit weight of the total material using estimated-fit density Interference Coefficient versus gravel content curves derived from the data of Garga and Madureira (1985)

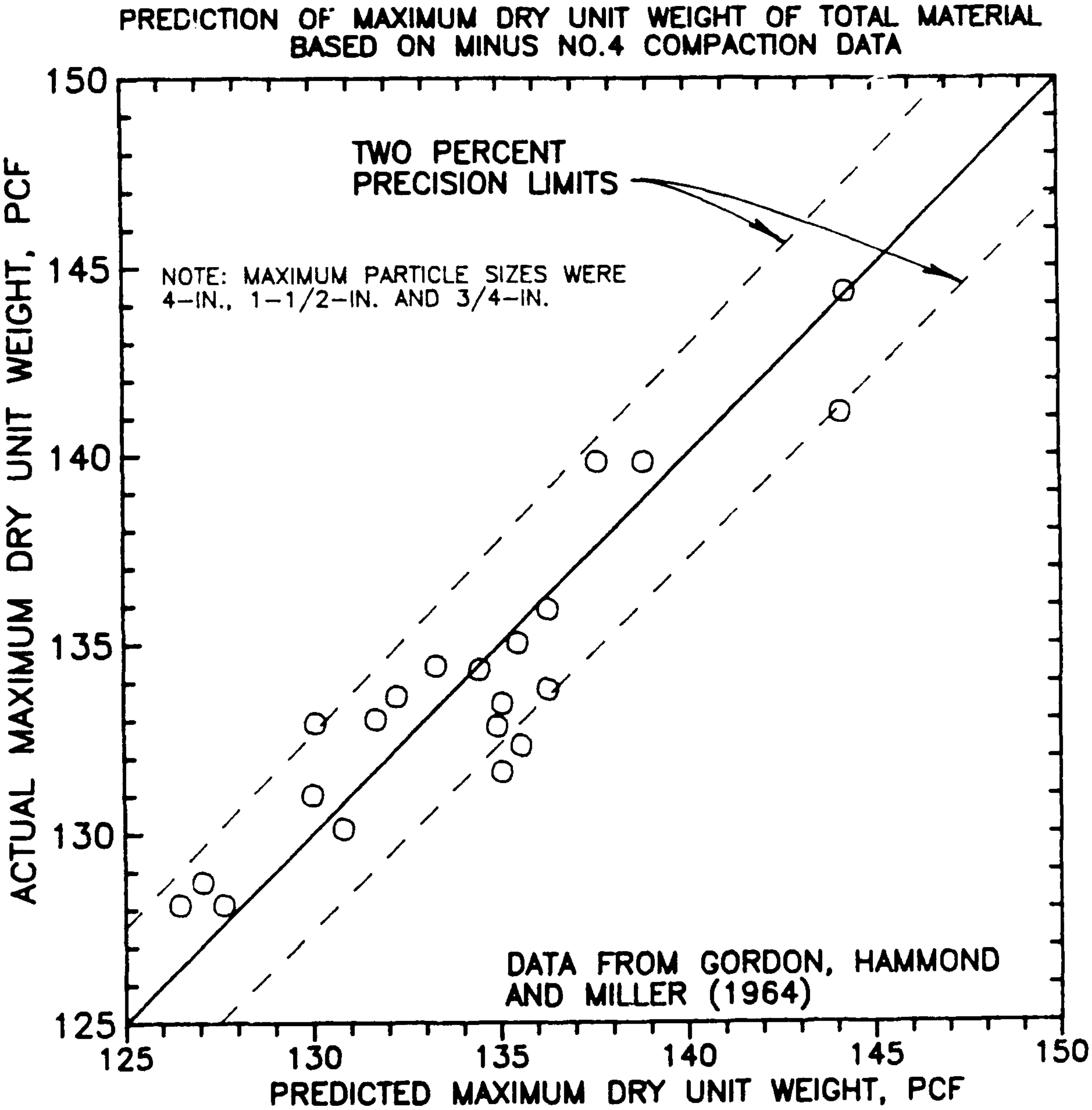


Figure 211. Prediction of maximum dry unit weight of the total material using estimated-fit density Interference Coefficient versus gravel content derived from the data of Gordon, Hammond and Miller (1964)

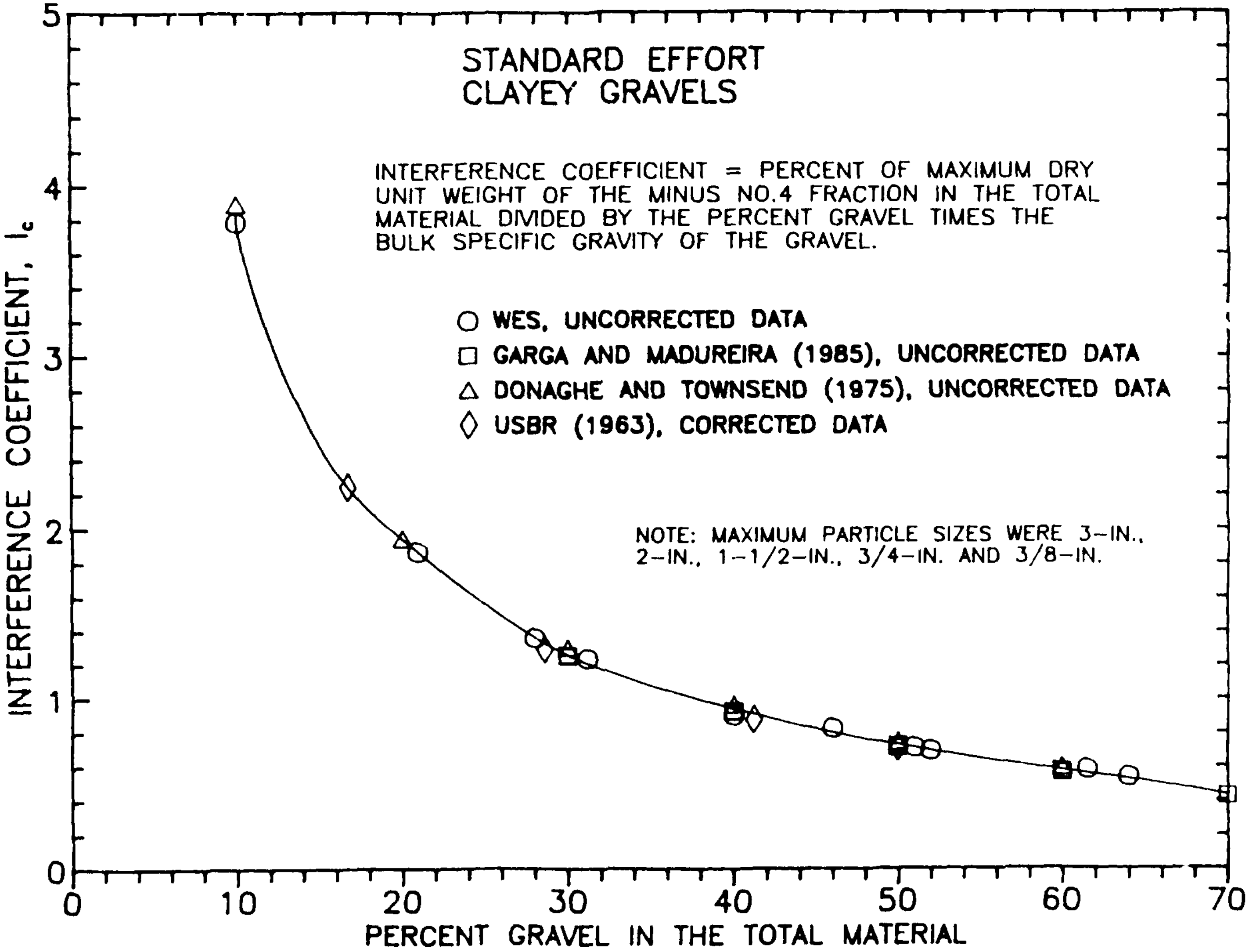


Figure 212. Density Interference Coefficient versus gravel content curve fit to standard effort compaction data on clayey gravels obtained from several investigators

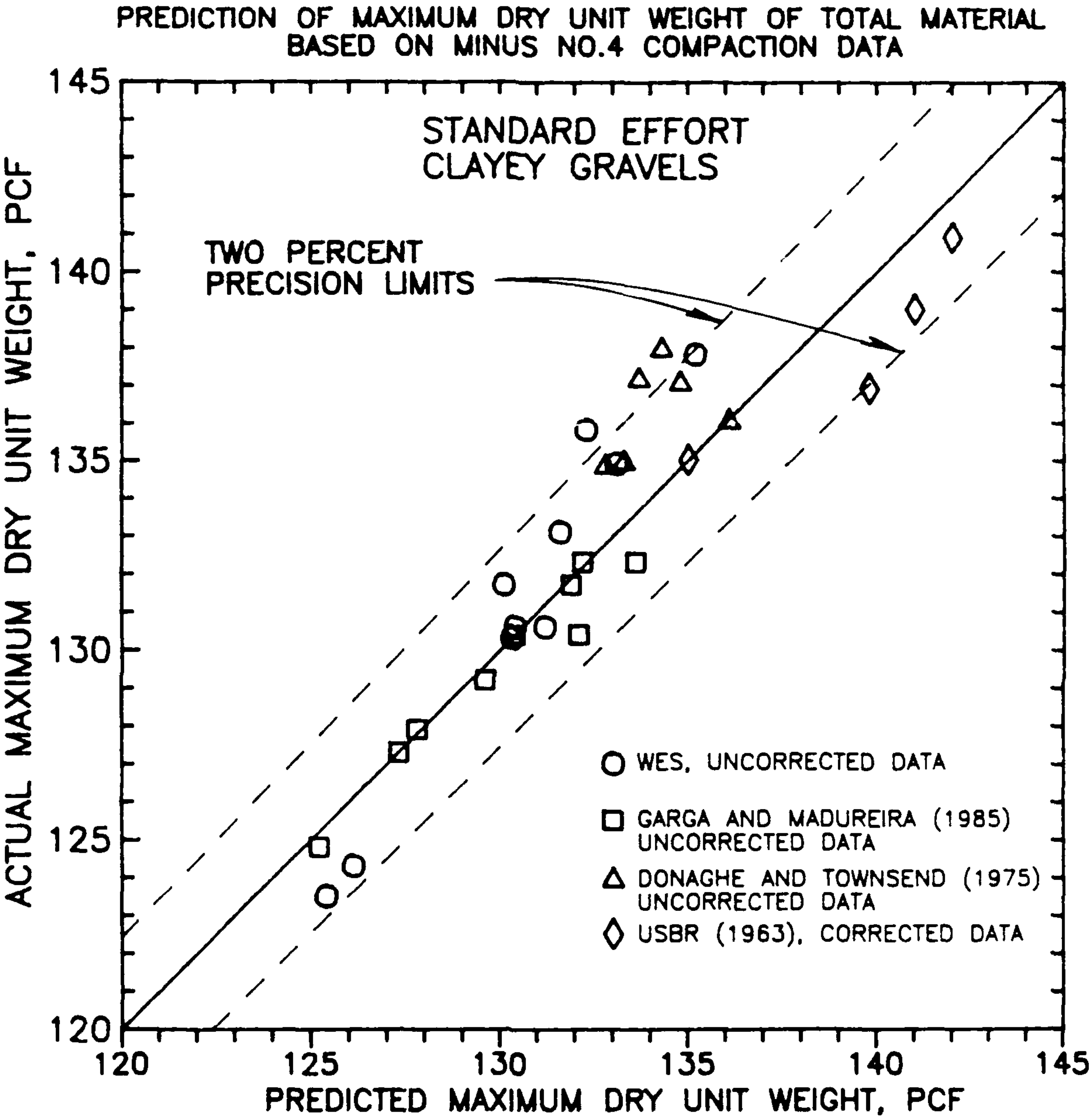


Figure 213. Prediction of maximum dry unit weight of the total materials of Figure 210 using the indicated density Interference Coefficient curve

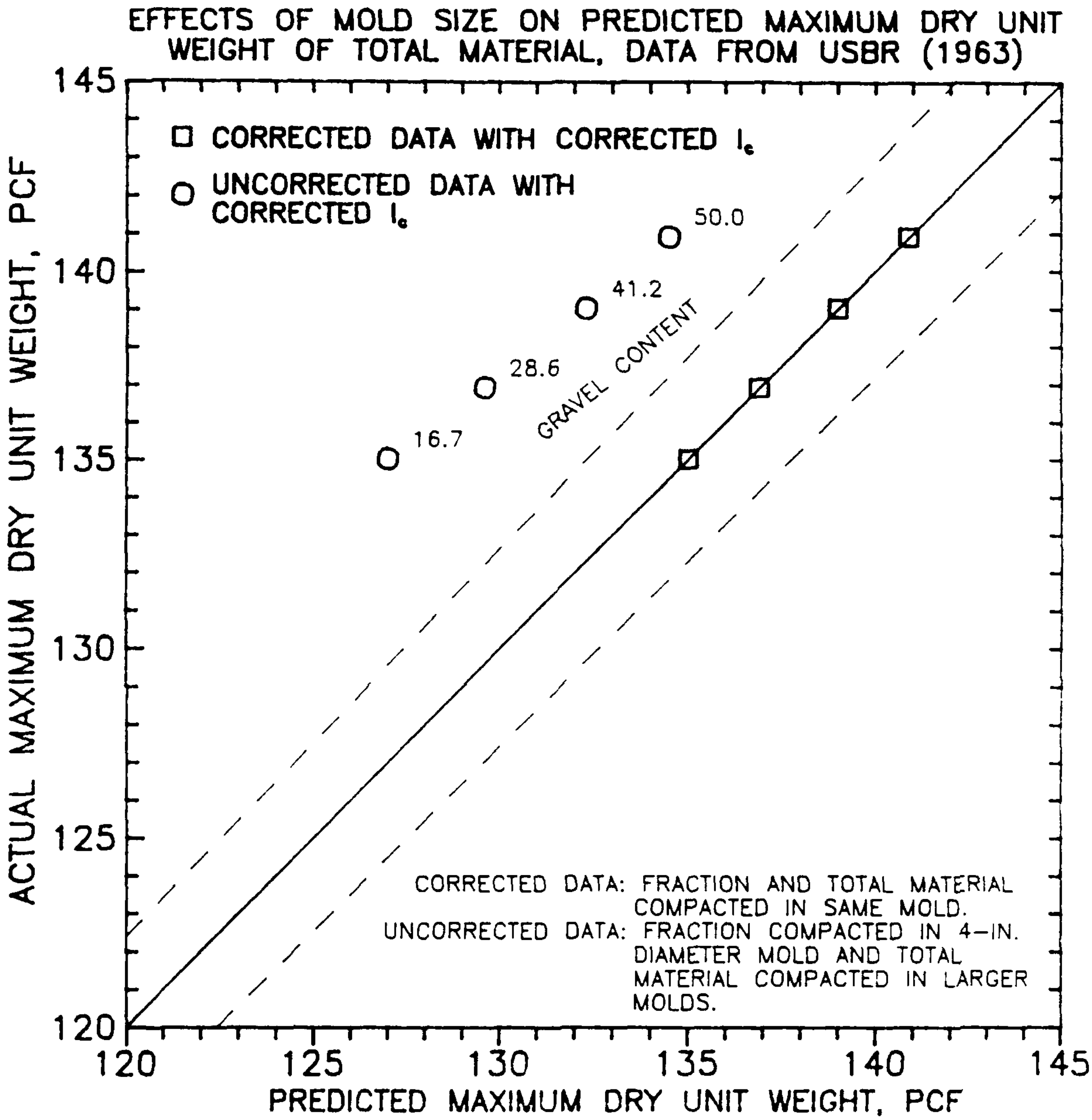


Figure 214. Example of error introduced in predicted values of maximum dry unit weight of the total material by use of density Interference Coefficients corrected for equipment size effects with uncorrected maximum dry unit weight of the finer fraction

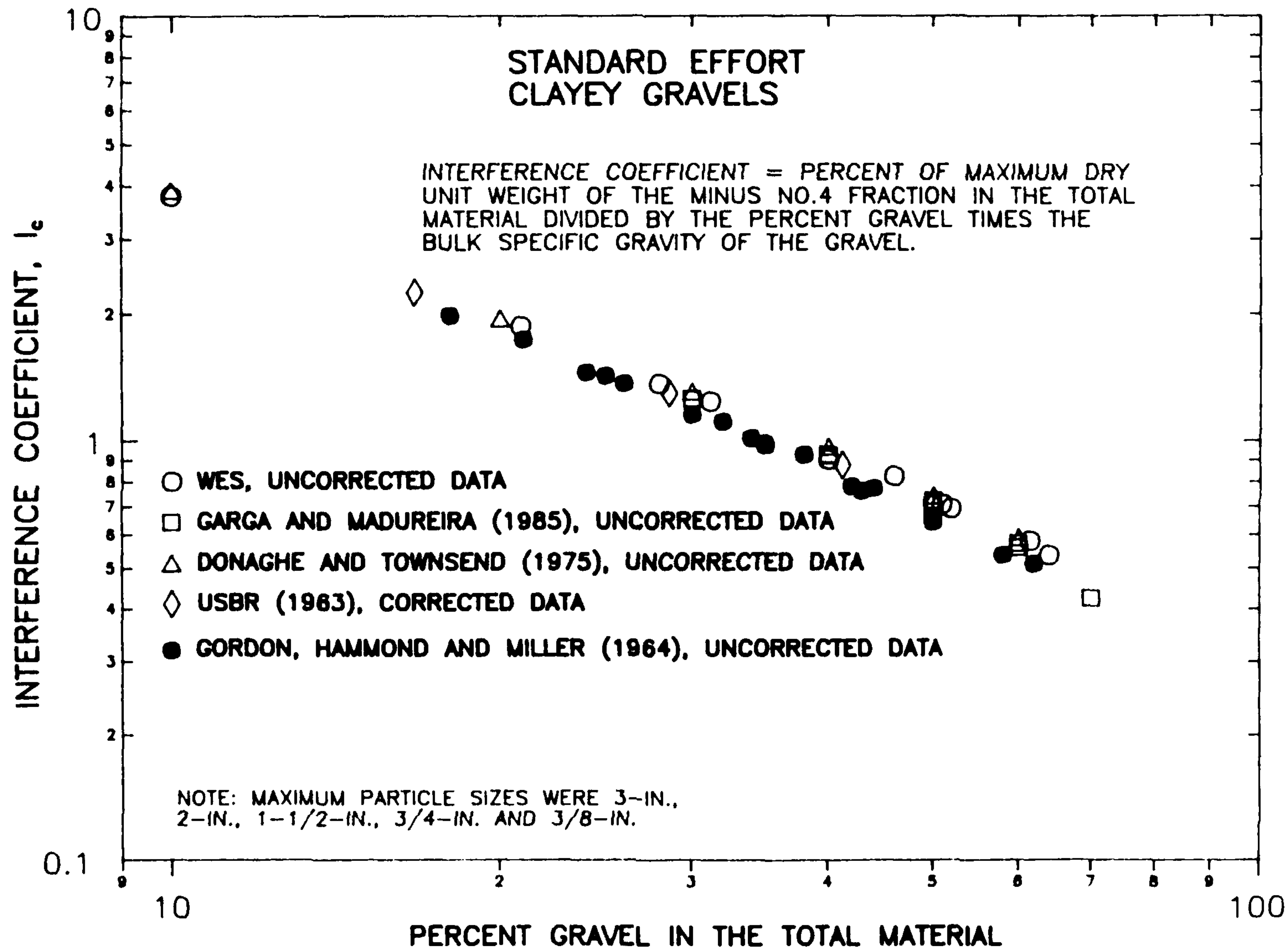


Figure 215. Density Interference Coefficient curve of Figure 210 plotted in log-log coordinates

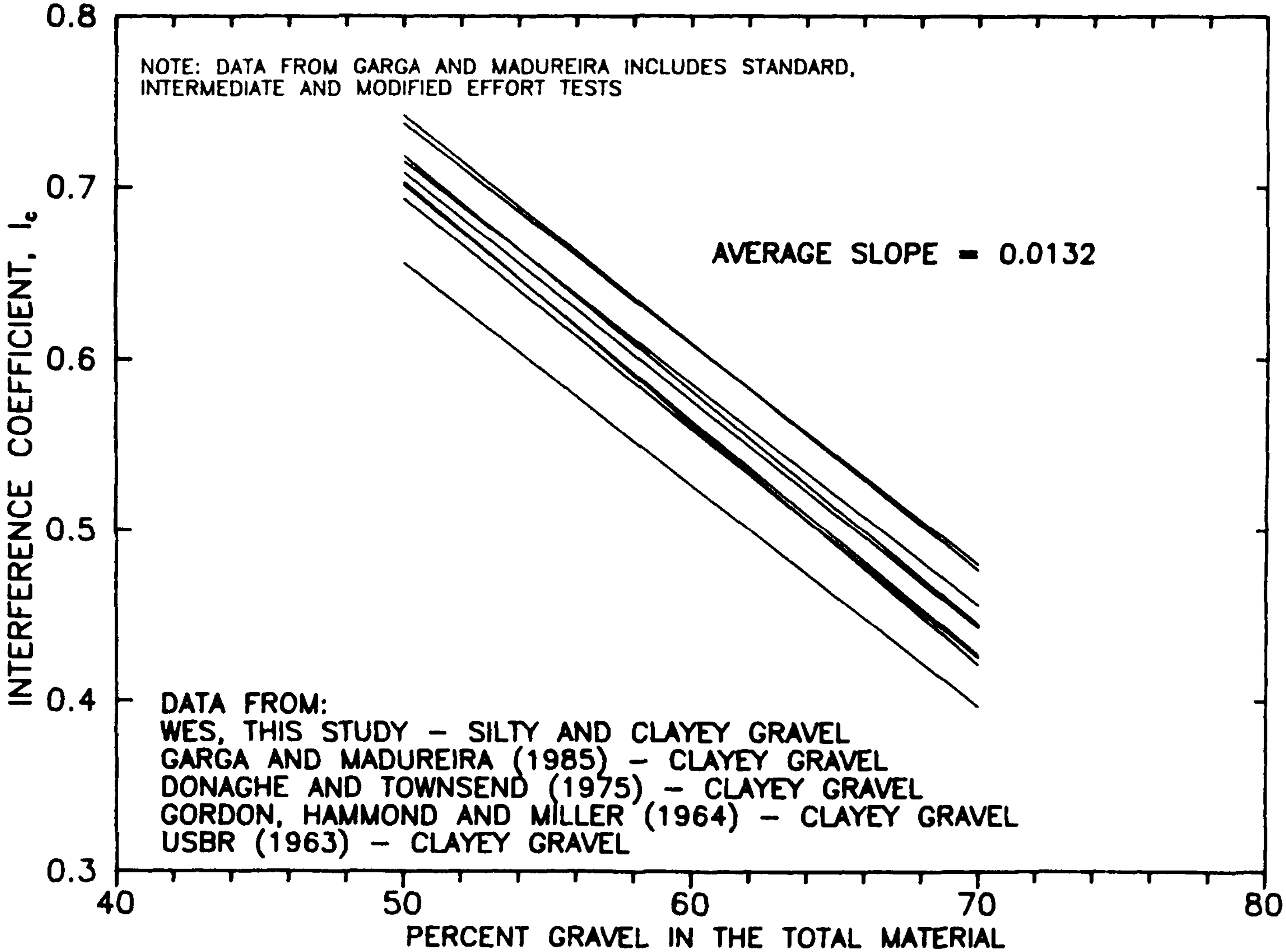


Figure 216. Slope of Density Interference Coefficient versus gravel content curves at gravel contents of 50 to 70 percent

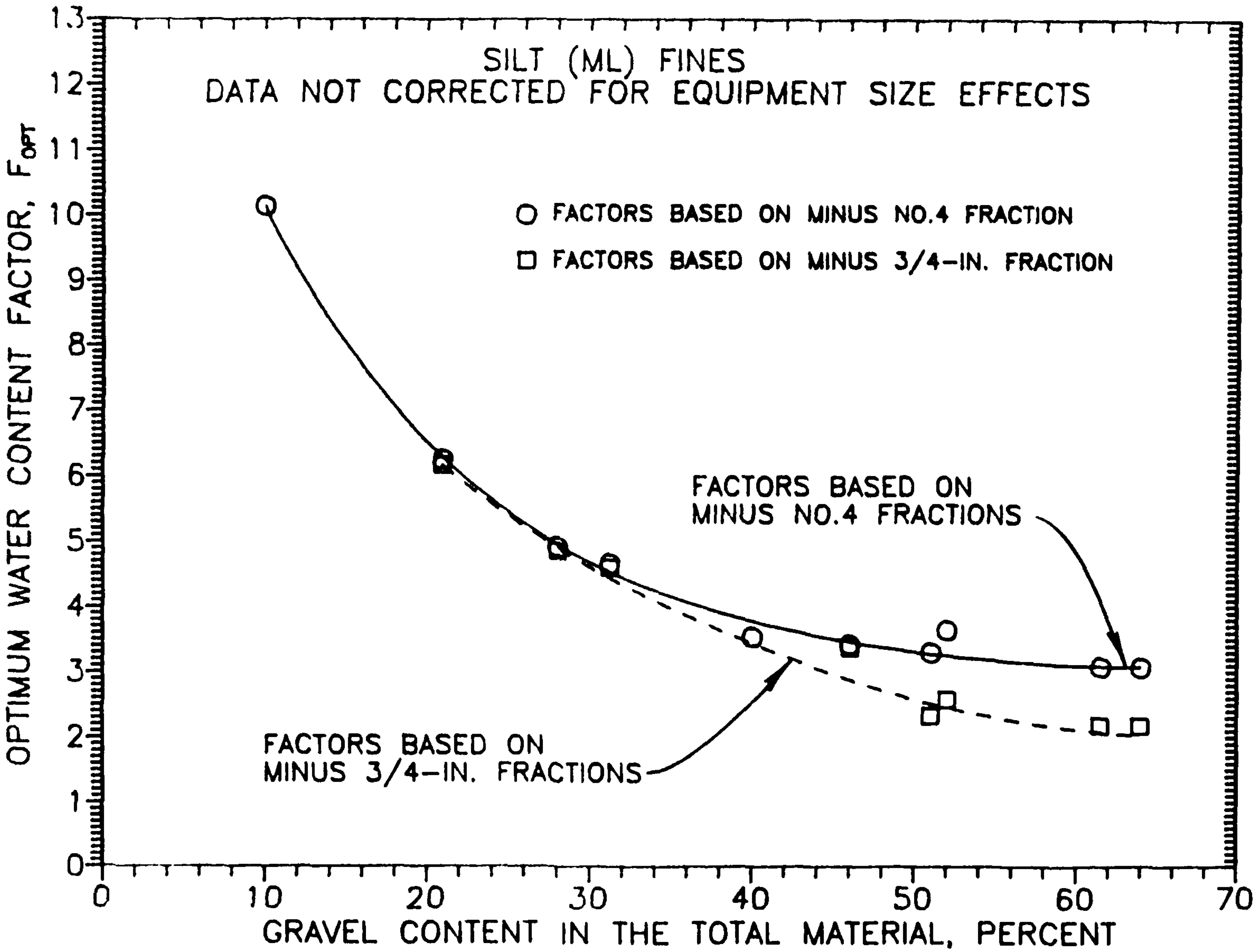


Figure 217. Optimum water content factor versus gravel content in the total material, silt fines, uncorrected data, this study

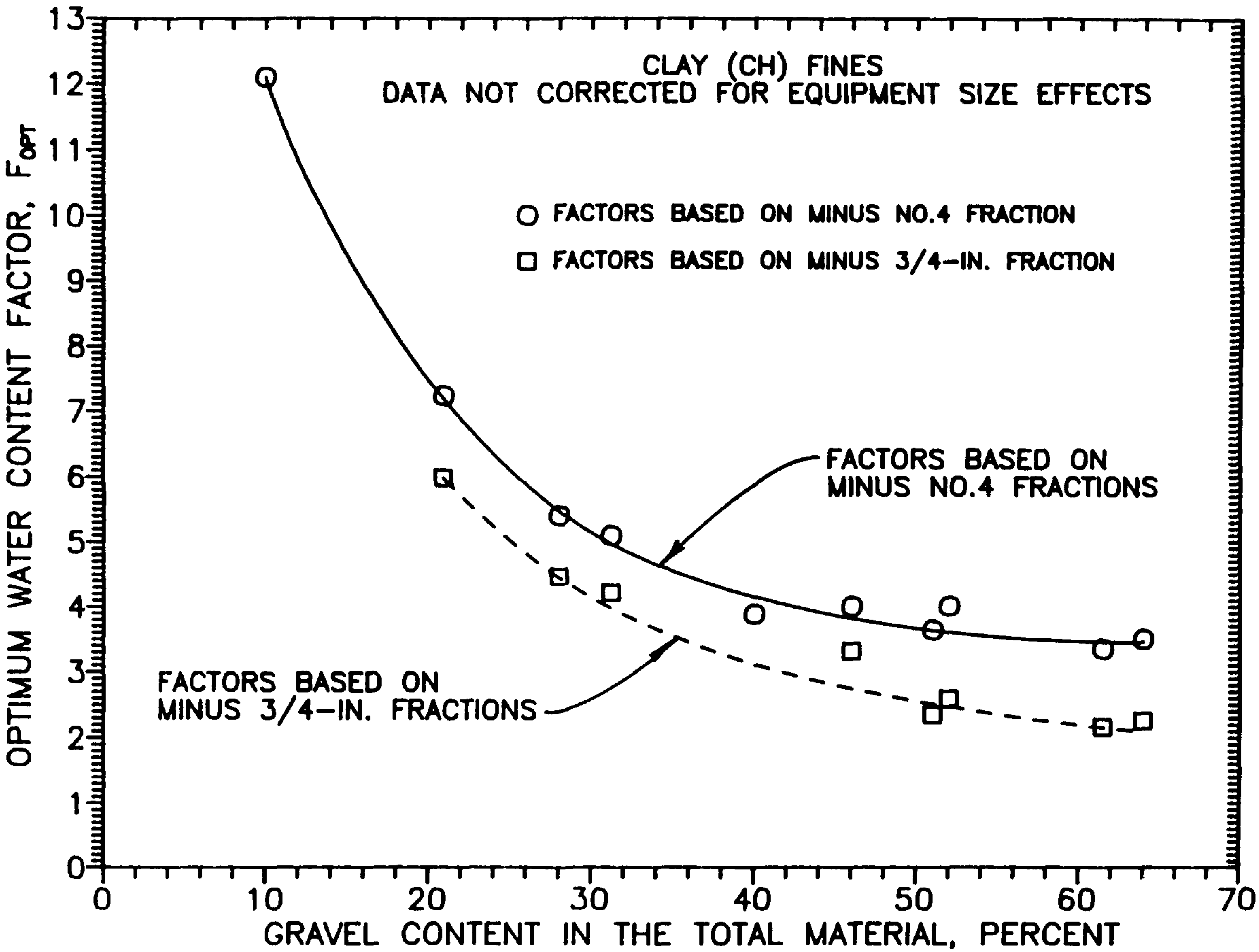


Figure 218. Optimum water content factor versus gravel content in the total material, clay fines, uncorrected data, this study

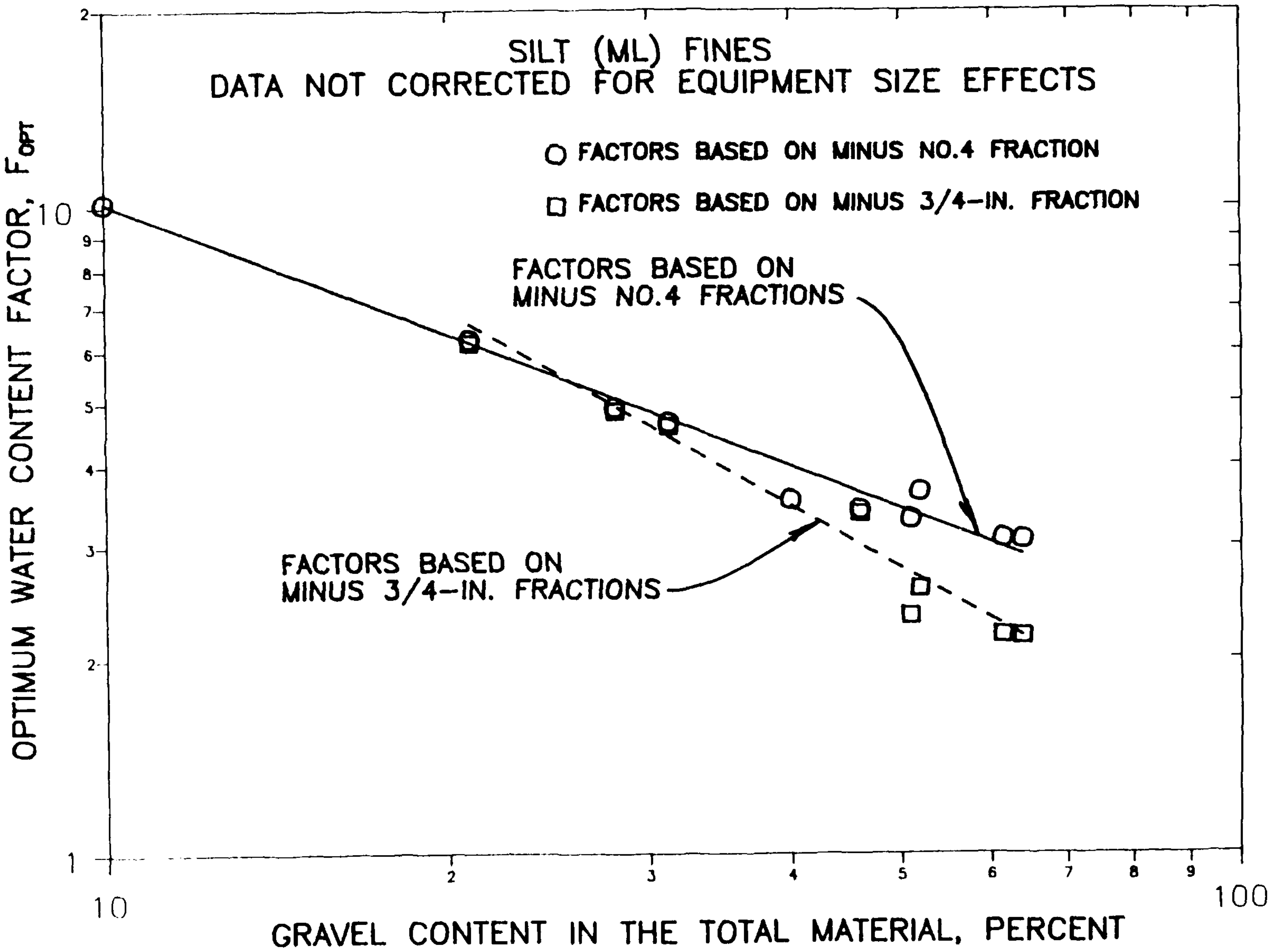


Figure 219. Optimum water content factor versus gravel content in the total material plotted in log-log coordinates, silt fines, uncorrected data, this study

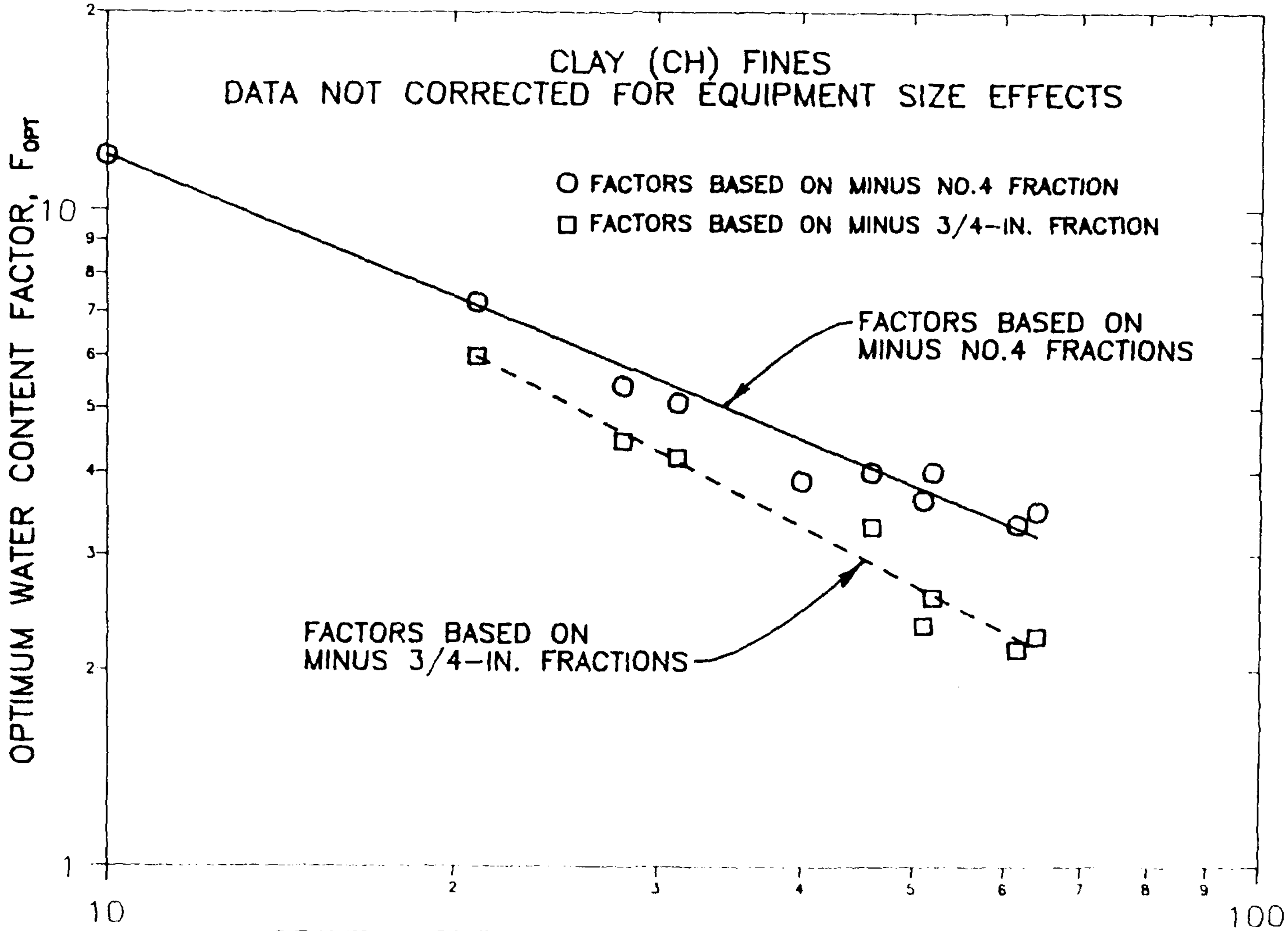


Figure 220. Optimum water content factor versus gravel content in the total material, plotted in log-log coordinates, clay fines, uncorrected data, this study

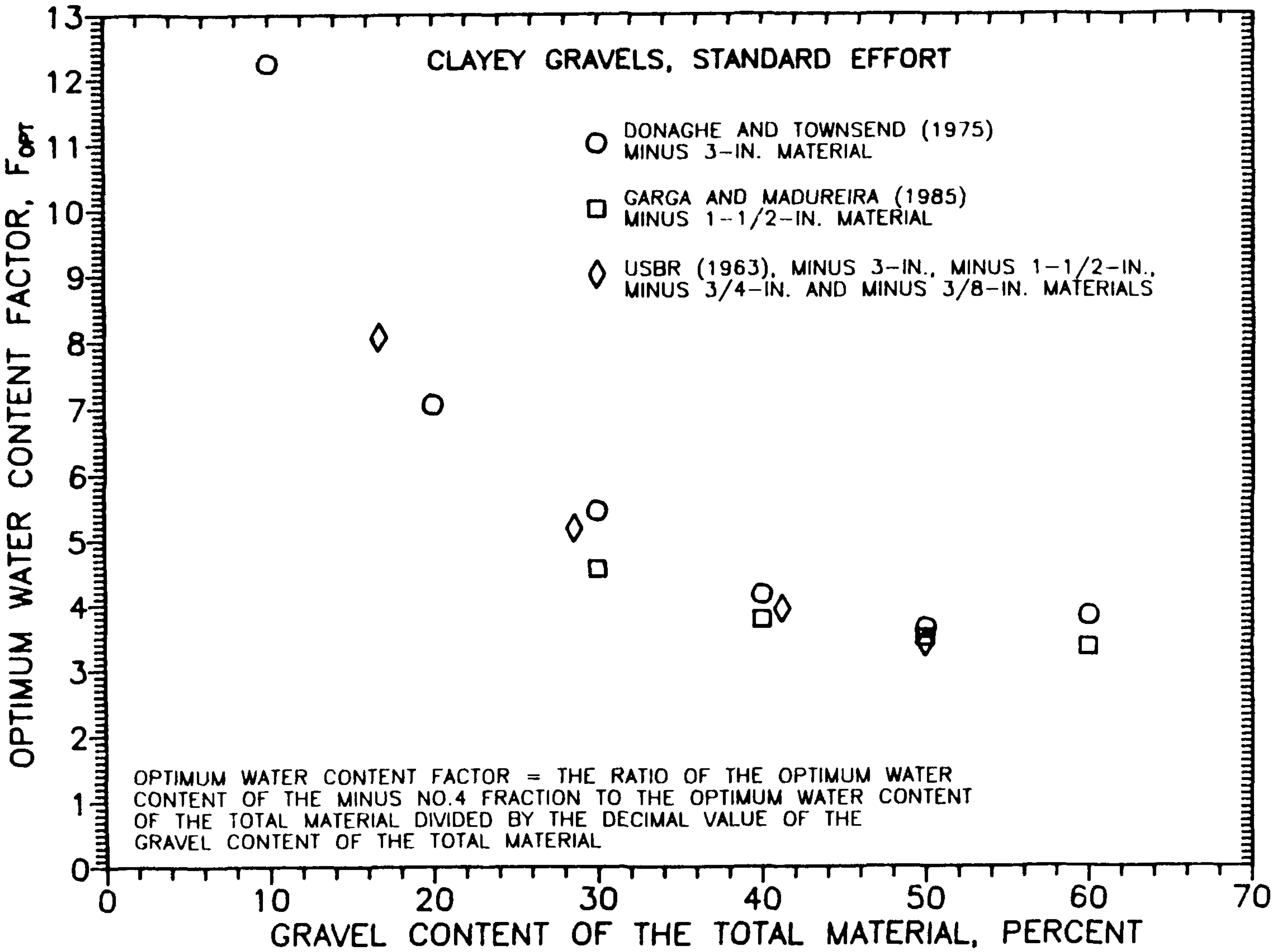


Figure 221. Optimum water content factor versus gravel content in the total material derived from the data of the USBR (1963), Donaghe and Townsend (1975) and Garga and Madureira (1985)

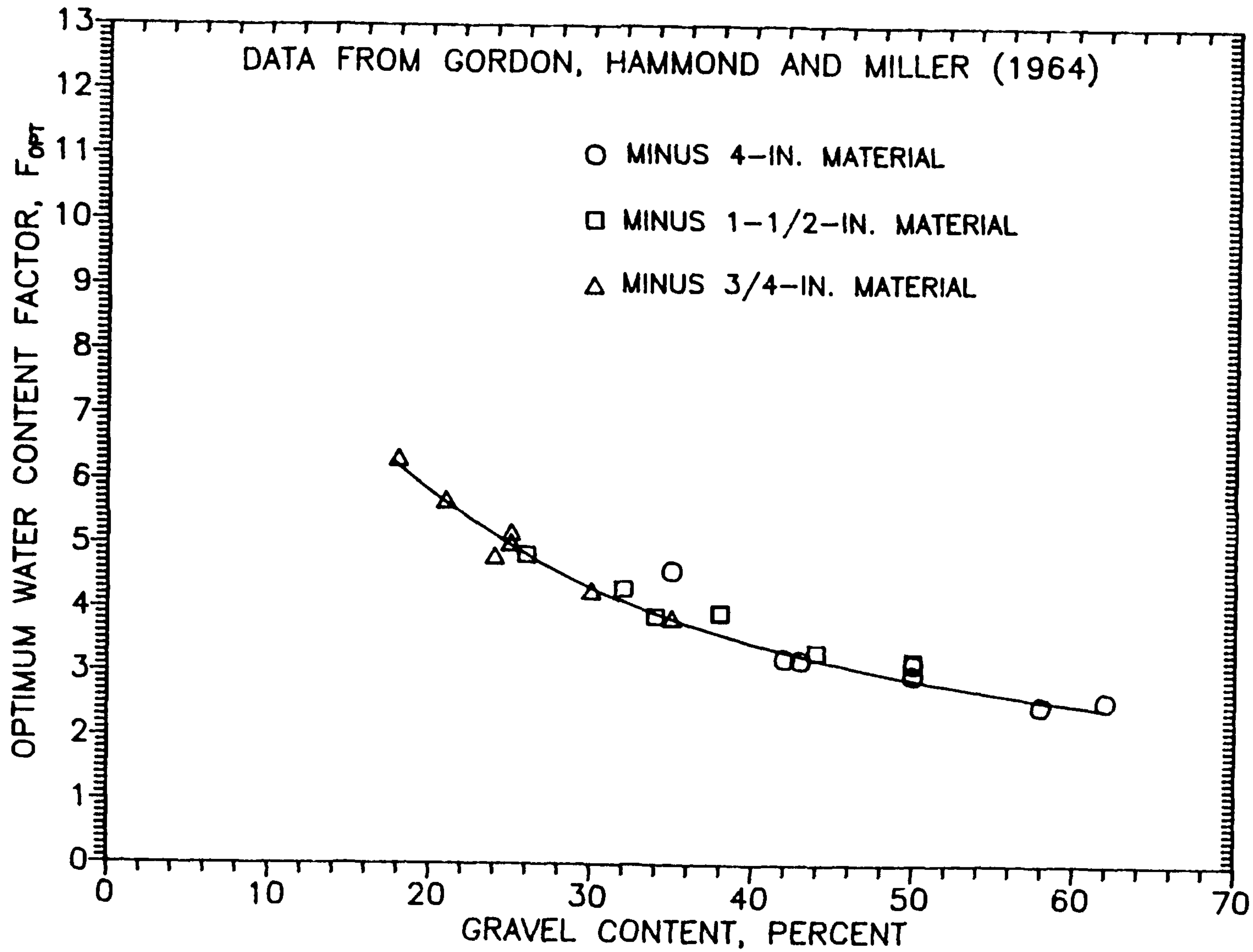


Figure 222. Optimum water content factor versus gravel content in the total material derived from the data of Gordon, Hammond and Miller (1964)

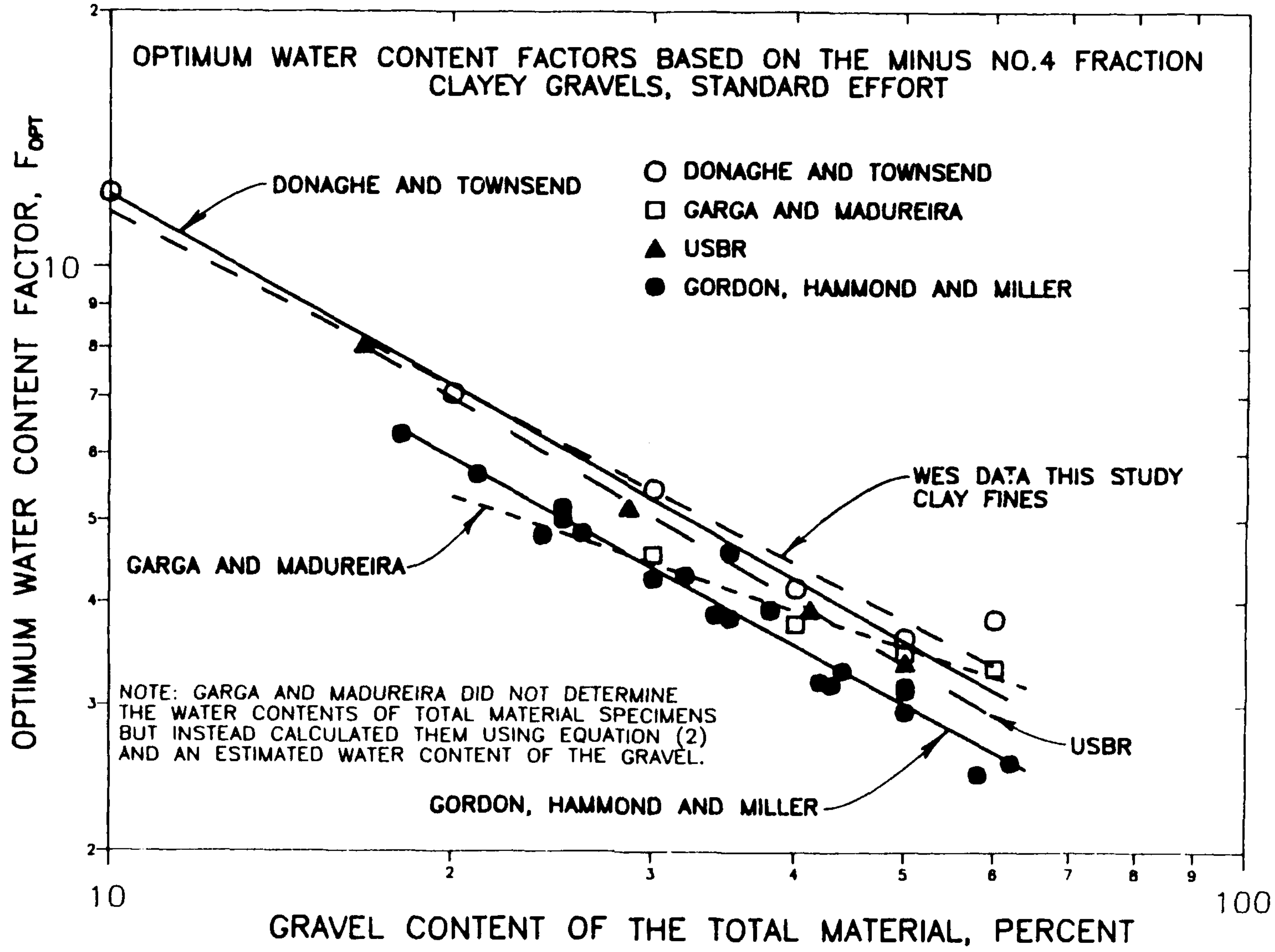


Figure 223. Comparison of relationships of optimum water content factor versus gravel content in the total material among several investigators

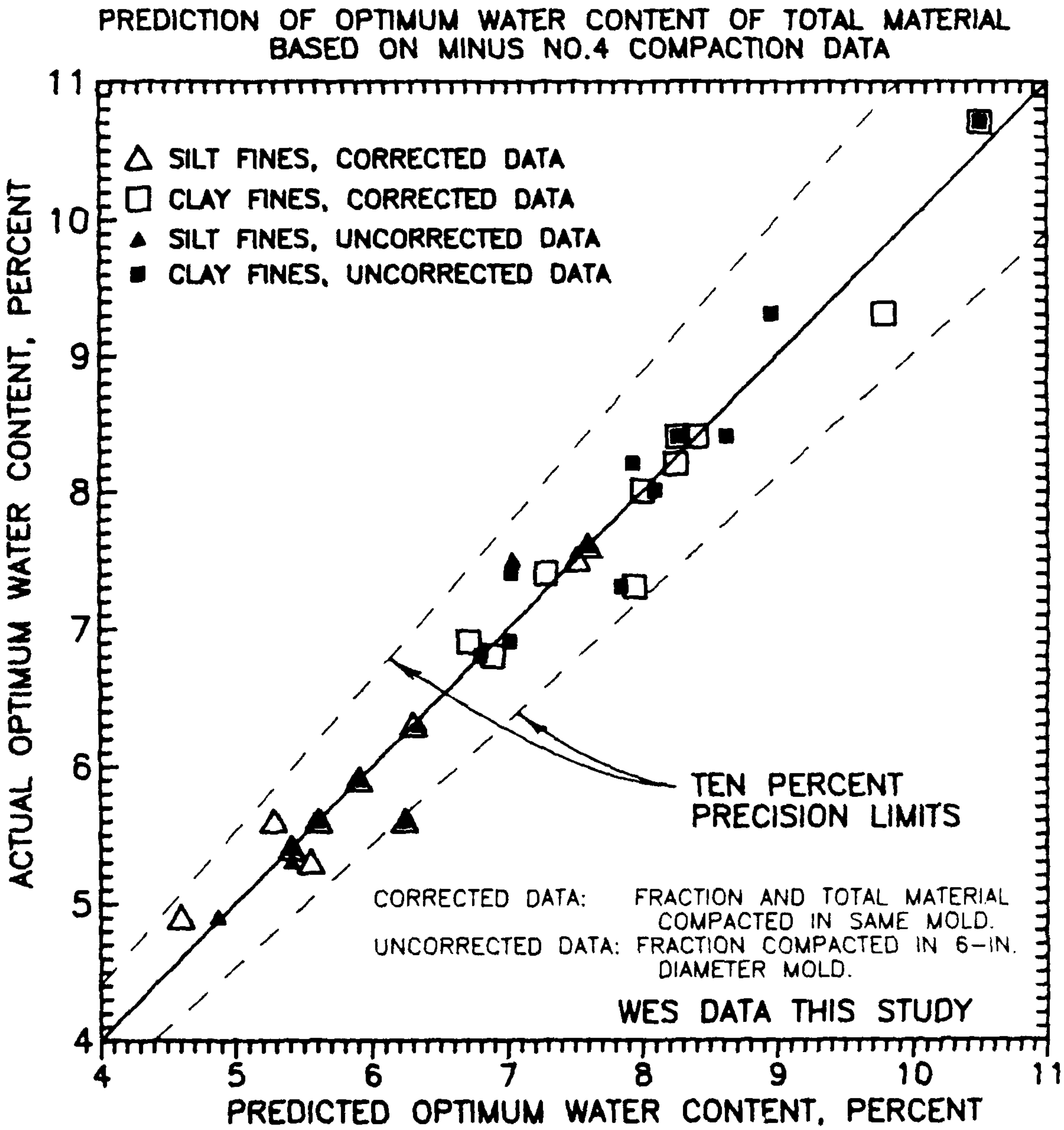


Figure 224. Prediction of optimum water content of the total material using optimum water content factors based on the minus No.4 fraction

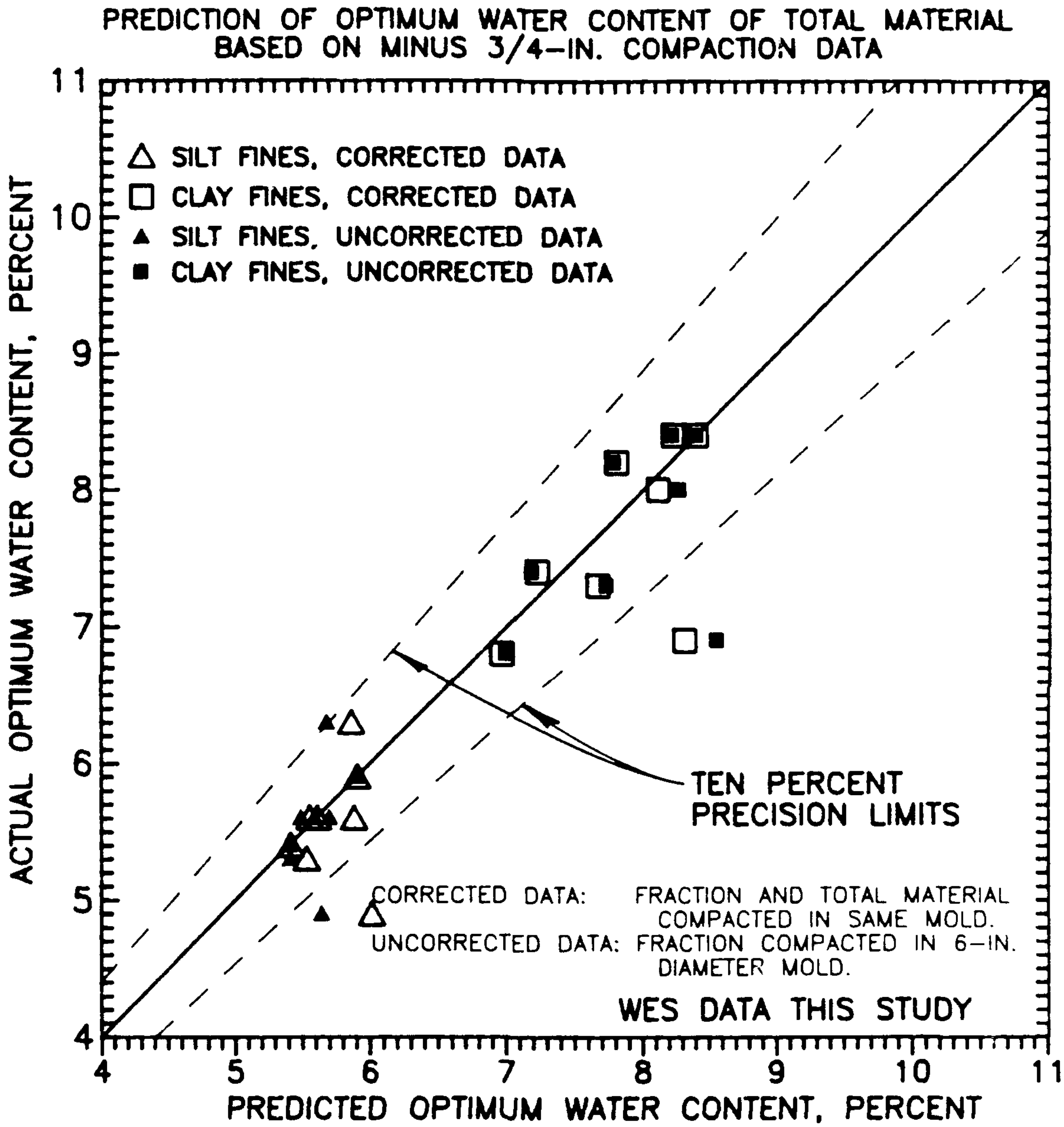


Figure 225. Prediction of optimum water content of the total material using optimum water content factors based on the minus 3/4-in. fraction

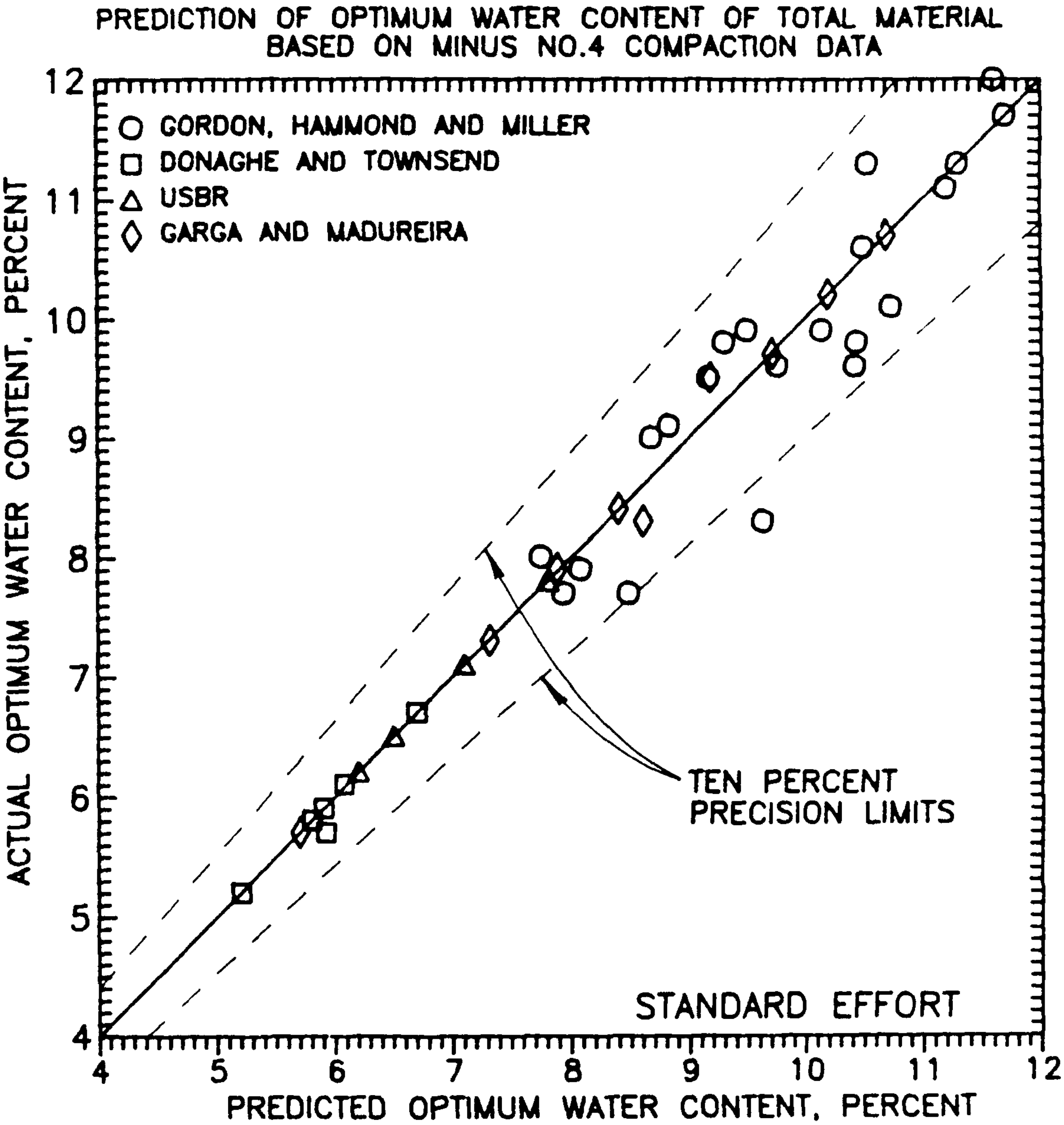


Figure 226. Prediction of optimum water contents of total materials tested by previous investigators using optimum water content factors based on the minus No.4 fraction

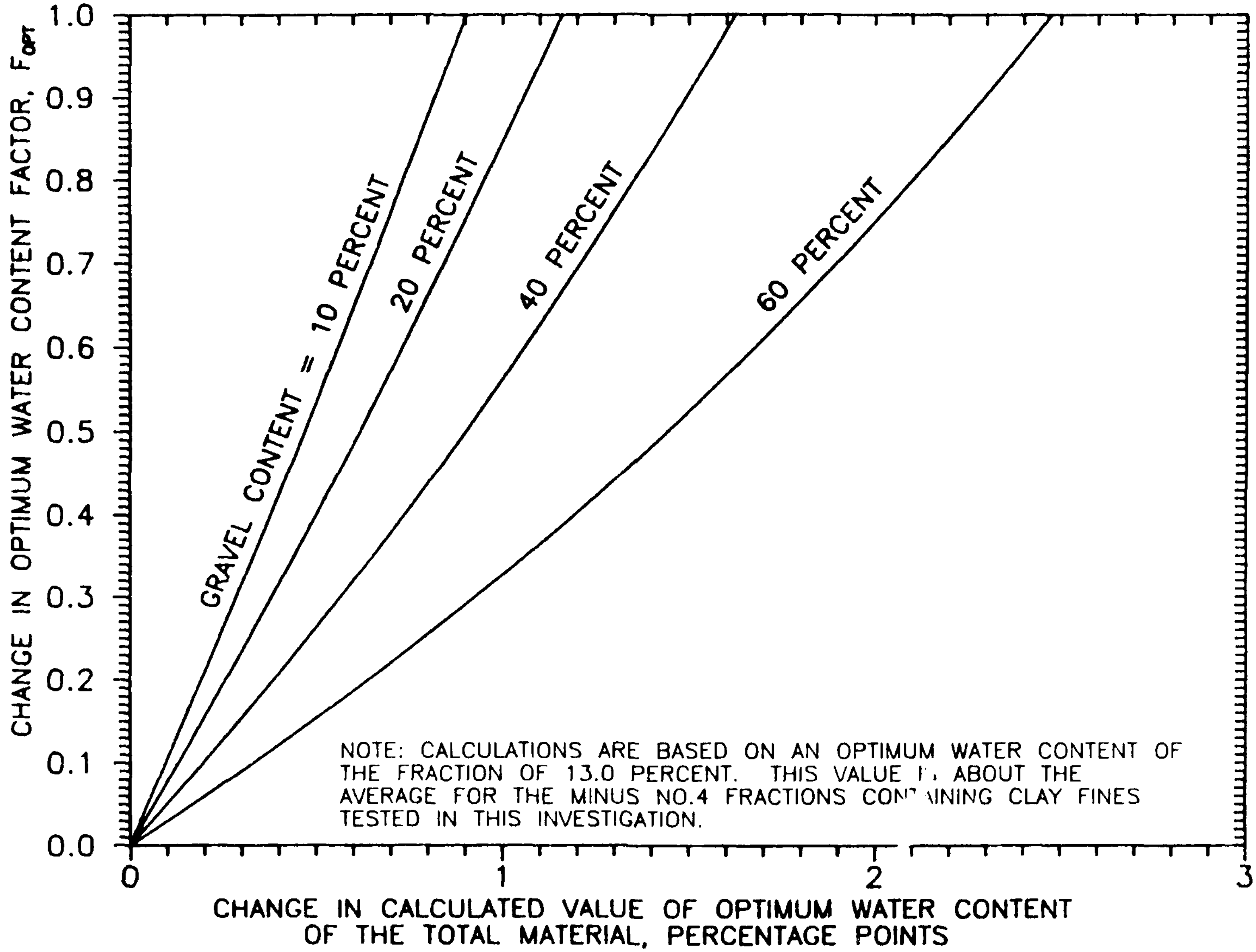


Figure 227. Sensitivity of predicted value of optimum water content to change in value of optimum water content factor

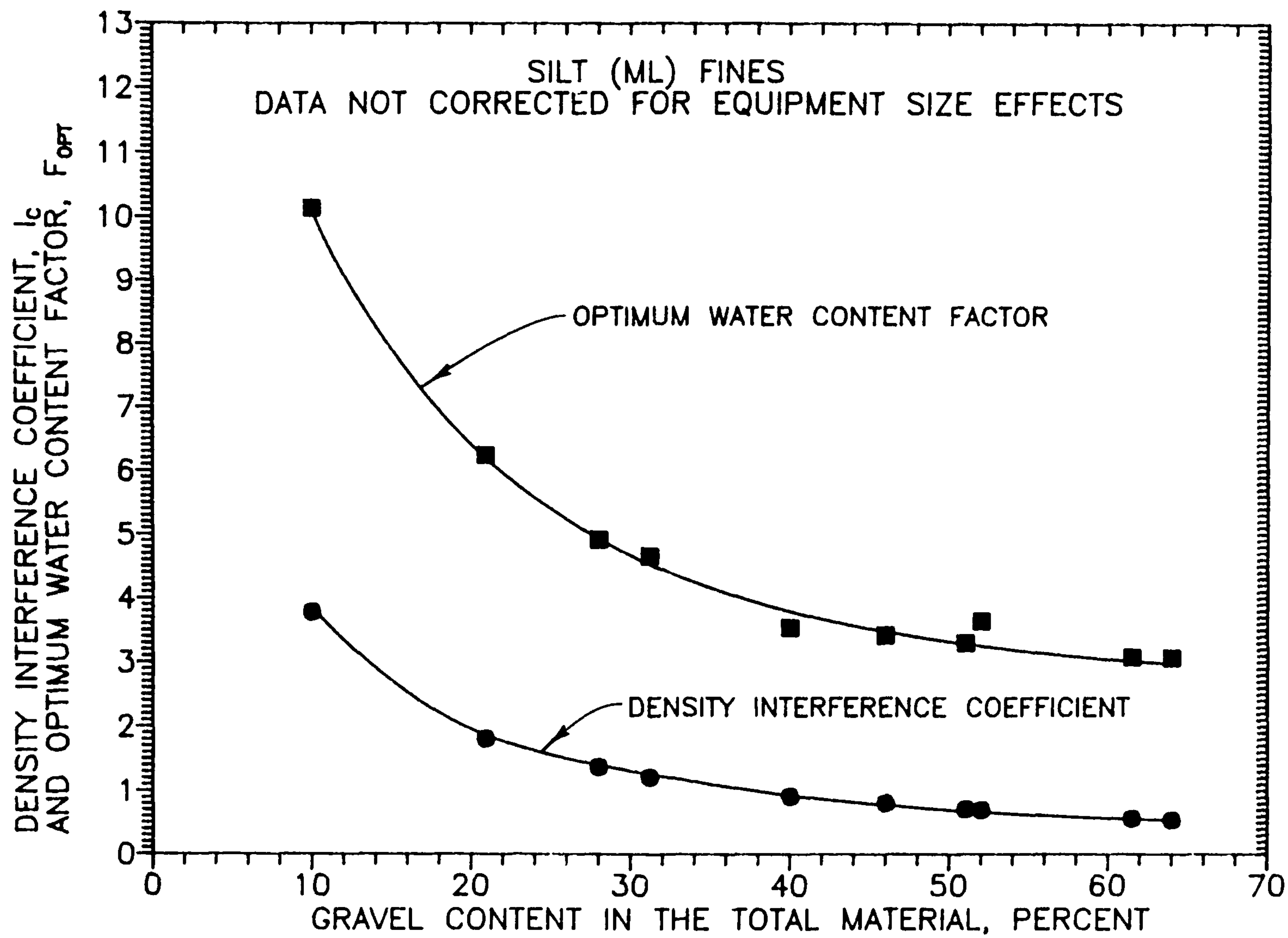


Figure 228. Comparison of density Interference Coefficients, I_c, and Optimum water content factors, F_{opt}, versus gravel content in the total material, silt fines, uncorrected data, this study

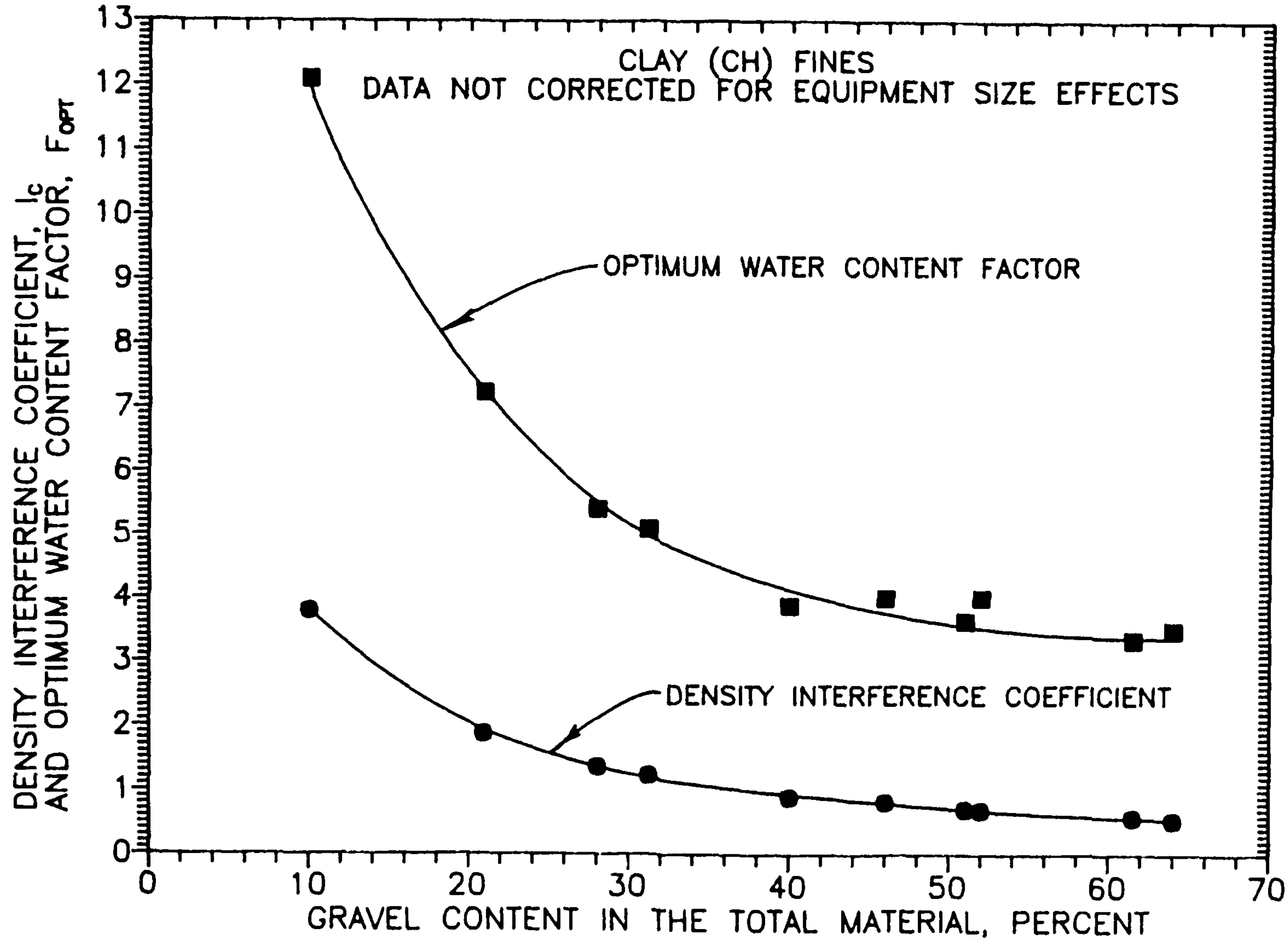


Figure 229. Comparison of density Interference Coefficients, I_c, and Optimum water content factors, F_{opt}, versus gravel content in the total material, clay fines, uncorrected data, this study

APPENDIX A: RECOMMENDED COMPACTION TEST FOR EARTH-ROCK MIXTURES

Introduction

1. This laboratory compaction method covers the determination of the relationship between the water content and unit weight of soils containing particles larger than the 3/4-in. sieve and finer than the 3-in. sieve when compacted using standard compactive effort in a mold of a given size with a 131.4-lb rammer dropped from a height of 12-in.

2. Two procedures are provided. The procedure used shall be based on the gradation of the soil as follows:

a. Procedure A:

Mold- 12.00-in. diameter by 12.00-in. high

Soil- Material passing 2-in. sieve

b. Procedure B:

Mold- 18.00-in. diameter by 18.00-in high

Soil- Material passing 3-in. sieve

3. This test method will generally produce well defined compaction curves for non-free draining soils. If this method is used for free draining soils the maximum unit weight may not be well defined.

4. If less than 5 percent by weight of the total sample is finer than the No. 200 sieve, maximum unit weight shall be determined by vibratory methods.

Apparatus

5. The apparatus consists of the following:

a. Mold assembly. The interchangeable molds shall be cylindrical in shape, made of rigid metal, and be within the capacity and dimensions indicated in 2a. and 2b. The molds may be of the split type equipped with hinges and a means of securely locking the two halves together to form a cylinder. Each mold shall have a detachable extension collar made of rigid metal. The extension collar shall have a diameter equal to that of the mold and shall extend at least 2.0-in. above the top of the mold. The extension collar may be equipped with an easily detachable upper section constructed of a thin metal to aid in placing all of the soil for the final layer in the mold assembly prior to compaction. Molds and collars shall be equipped to individually clamp to the mold assembly base plate. The base plate shall be planar within the area enclosed by the molds and shall be constructed so the mold assembly can be rotated and moved forward and backward on a lubricated support plate. Provision shall be made to limit lateral movement of the mold during rotation to less than 0.04-in. and to limit forward and backward movement of the mold so the rammer can strike no closer than 0.1-in. from the inside surface of the mold at its smallest diameter. In addition, provision shall be made to move the 18-in. diam mold forward so central blows may be applied with the center of the rammer following a circular path 3.0 ± 0.1-in. from the side of the mold. The base plate shall have a raised edge with an inner diameter equal to that of the outer diameter of the 18-in. diam mold so the mold can be secured and centered on the base plate. A metal ring with appropriate dimensions shall be provided to accomplish the same purpose for the 12-in. diam mold. The ring shall fit securely against the raised edge of the base plate. The base plate shall be equipped with capstan handles or other devices to provide a means of rotating the mold assembly and to move it forward and backward so rammer blows may be evenly distributed over layer surfaces. The mold assembly support plate shall be attached to a rigid foundation equivalent to a 2000-lb or larger concrete block. Contact surfaces of the support plate and mold assembly base plate shall be planar and lubricated with grease or other suitable lubricant to decrease friction.

b. Mold Dimensions

(1) Mold, 12-in. diam. A mold having a 12.00 ± 0.02-in. average inside diameter, a height of 12.00 ± 0.02-in. and a volume of 0.785 ± 0.004-ft^3.

(2) Mold, 18-in. diam. A mold having a 18-in. ± 0.02-in. average inside diameter, a height of 18.00 ± 0.02-in. and a volume of 2.651 ± 0.009-ft^3.

(3) The average internal diameter, height, and volume of each mold shall be determined before initial use. The mold volume shall be calculated from the average of at least six internal diameter measurements taken at the top and bottom of the mold and six height measurements made to the nearest 0.01-in. The determined volume shall be used in computing unit weights.

c. Mold assembly Harness. A device for moving the mold and mold assembly using a forklift.

d. Rammer. A mechanically operated rammer having a mass of 131.4 ± 0.1-lb. The rammer shall consist of a foot attached to a 15-ft long, 2-in. O.D. diameter metal tube. The rammer shall have a fixed vertical position relative to the mold assembly and shall fall freely through a distance of 12 ± 0.05-in. from the surface of the specimen. The striking face (foot) of the rammer shall be planar and circular with a diameter of 6.00 ± 0.02-in.

e. Compactor. A mechanical device for controlling operation of the rammer. The compactor shall be a rigid metal frame attached to the foundation upon which the mold assembly support plate rests. It shall be located to provide the fixed vertical position required for operation of the rammer and shall be equipped with appropriate devices to pick up the rammer and provide a free drop of 12 ± 0.05-in. The drop height shall be adjustable so it may be corrected, when necessary, to meet the specification. The compactor shall be equipped to automatically provide identical drop heights regardless of the height of soil in the mold. The compactor shall be provided with two low friction guide sleeves or bearings located at least 2-ft apart to assure a vertical drop of the rammer. The guide sleeves or bearings shall form a circular area having a diameter 0.2 ± 0.01-in. greater than the diameter of the metal tube connected to the rammer foot. Provision shall be made for the compactor to clear the rammer from the mold at the end of a cycle of blow applications or at any time the test is stopped. A control shall be included to stop the test at any time. The compactor shall be equipped with a positive mechanical means to support the rammer when not in operation. Additional equipment for the compactor such as a jog control, a counter, and a variable speed motor may be added to the compactor to aid in controlling the rammer.

f. Compactor calibration. The compactor shall be calibrated periodically to check that the rammer is dropping freely for a distance of 12.00 ± 0.05-in. Assemble the compactor as if for a test and place rags or other suitable material in the mold to absorb the impact of the rammer. Initiate operation of the rammer and after 10 blows are applied and while the compactor continues to operate, observe whether binding of the rammer is occurring against the guide sleeves or bearings used to assure a vertical drop of the rammer. If binding or excessive friction occurs, it may be necessary to move the bushings or bearings or to straighten the rammer. Check the drop height by marking or placing a piece of tape on the rammer and measuring its travel using a cathodometer or other suitable measuring device. Adjust the drop height if necessary and verify by repeating the procedure.

g. Balances. Heavy duty platform balances readable to 0.1-lb with capacities of 250 and 1000-lb.

h. Drying oven. Forced-draft type, 10-ft^3 minimum capacity, thermostatically controlled to maintain a uniform temperature of 110 ± 5°C.

i. Drying Pans. Heavy duty drying pans with a combined capacity of at least 5.0-ft^3 constructed of a corrosion resistant metal.

j. Containers. Corrosion resistant containers having a capacity of at least 1-ft^3 and equipped with air-tight lids.

k. Sieves. Screen trays containing U.S. Standard Sieve screens ranging from 4-in. to No. 4 sieve sizes and a mechanical screen shaker. Sieve sizes of 3/8-, 1/2-, 3/4-, 1-, 1-1/2-, 2-, 3-, and 4-in. are normally required.

l. Straightedge. A steel straightedge at least 20-in. long, 3/8-in. thick and 1-in. wide with a beveled edge.

m. Specimen batching equipment. Mixing pans, scoops, 1/4-in. hard ware cloth, buckets and the like for batching minus No. 4 sieve fractions of samples at desired water contents.

n. Miscellaneous equipment. Wire brush, rubber-headed maul, trimming knife, metal rule, cathodometer, shovel, fans, wire brush, broom, tamper etc.

Amount of Material

6. At least 900-lb of minus 2-in. sieve size soil are required for the 12-in. diam mold test (Procedure A) and at least 3000-lbs of minus 3-in. sieve size soil are required for the 18-in. diam test (Procedure B). Because of the disparity in amounts of material, the decision as to the procedure to use and therefore the amount of material to send to the laboratory shall be made in the field based on a visual classification or by other means.

Processing of Soil

7. Spread the entire sample on a smooth, clean, dry floor area and allow it to air-dry. The use of fans and frequent turning of the material with a shovel will speed air-drying. Other means such as ovens and heat lamps, may also be used to accelerate drying if the drying temperature does not exceed 60-deg C.

8. Visually classify the sample and record the classification along with other sample identification information on the test worksheet.

9. Reduce aggregations of finer material formed during drying to particles smaller than the No. 4 sieve size using a tamper. Use a wire brush or other suitable means to remove fine grained material adhering to larger particles.

10. The rigorously correct manner in which to separate the material into its various sieve sizes would be to oven-dry the entire sample before sieving. However, because the air-dry water content will be generally less than two percent for minus No. 4 sieve material and even less for the gravel fraction, only negligible error results from determining sieve fractions by sieving the air-dry sample. Therefore, percentages by weight determined on

the air-dry sample as described below will be used as if they are equivalent to percentages by weight of oven-dry material.

11. Pass the total air dried sample over the 3-, 2-, 1 1/2-, 1-, 3/4-, 1/2-, and 3/8-in. and No. 4 sieves. Place the material retained on each sieve and that passing the No. 4 sieve in separate containers labeled with the appropriate size range.

12. Determine the weight of material retained on each sieve and that of the material passing the No. 4 sieve. Compute the percent by weight retained on each sieve and that passing the No. 4 sieve as follows:

$$\%\ \text{Retained} = \frac{\text{air-dry weight of material retained on sieve}}{\text{air-dry weight of total sample}} \times 100$$

Then calculate total percent gravel, P_g, by adding up percentages retained of gravel sizes (plus No. 4 sizes).

13. Determine the air dry water content of a representative sample of the plus No. 4 sieve and minus No. 4 sieve material. Also, perform tests to determine the bulk and apparent specific gravity of a representative sample of the plus No. 4 sieve material and the specific gravity of solids and Atterberg limits of a representative sample of the minus No. 4 sieve material.

Specimen Preparation

14. Calculate the amount of air dry soil to prepare for each test specimen as follows:

a. Procedure A (12-in. diam mold),

$$WT_{AD} = 0.9P_g(1 + W_g)\gamma_{dmax} + 0.9P_{NC4}(1 + W_{NC4})\gamma_{dmax}$$

where

WT_{AD} = required air-dry weight of soil

γ_{dmax} = estimated maximum dry unit weight of soil

w_g = air-dry water content of the plus No. 4 sieve material (gravel fraction) expressed as a decimal

w_{NO4} = air-dry water content of the minus No. 4 sieve material expressed as a decimal

P_g = total percent by weight of plus No. 4 sieve material (gravel) expressed as a decimal

P_{NO4} = percent by weight of minus No. 4 sieve material expressed as a decimal

b. Procedure B (18-in. diam mold),

$$WT_{AD} = =3.0P_g(1 + W_g)\gamma_{dmax} + 3.0P_{NO4}(1 + W_{NO4})\gamma_{dmax}$$

15. Prepare material for each specimen by batching the gravel and minus No. 4 sieve fractions separately.

a. Gravel, Gravel fractions for specimens to be tested using Procedure A shall have a maximum particle size of 2-in. Those tested using Procedure B shall have a maximum particle size of 3-in. For both procedures prepare 3 gravel batches (one for each layer) for each specimen by combining required amounts of each size fraction calculated as follows:

$$WT_{gf} = \frac{P_r Wt_{AD}}{3}$$

where

WT_{gf} = required air-dry weight of particular gravel size fraction

P_r = percent by weight retained on corresponding sieve size as determined in paragraph 11 above expressed as a decimal

b. Minus No. 4 sieve material. Prepare the minus No. 4 sieve material for each specimen in a single batch.

(1) The weight of air-dry minus No. 4 sieve material to prepare for the test specimen shall be obtained by the following calculation:

$$WT_{NO4} = P_{NO4}WT_{AD} + 10\ lb$$

where

WT_{No4} = required air-dry weight of minus No. 4 sieve material

(2) Thoroughly mix the air-dry minus No. 4 sieve material for the test specimen with a measured quantity of water sufficient to produce a water content 2 or 3 percentage points below the estimated optimum water content of the soil to be tested. The amount of water to be added shall be calculated as follows:

First, calculate the air-dry water content of the total specimen as follows:

$$W_{AD} = P_g W_g + P_{NO4} W_{NO4}$$

where

w_{AD} = air-dry water content of the total specimen expressed as a decimal

Then, calculate the dry weight of the total specimen as follows:

$$WT_D = \frac{WT_{AD}}{(1 + W_{AD})}$$

where

WT_D = dry weight of the total specimen

Finally, calculate the amount of water to be added to the air-dry minus No. 4 material as follows:

$$WT_{WA} = (W_t + W_e)WT_D - \frac{W_g P_g WT_{AD}}{(1 + W_g)} - \frac{W_{NO4}(P_{NO4} WT_{AD} + 10\ lb)}{(1 + W_{NO4})}$$

where

WT_{wa} = weight of water to be added to minus No. 4 sieve material

w_t = desired water content of total test specimen

w_e = estimated decrease in water content due to evaporation during batching, usually assumed to be 0.5 percentage points

(3) Thoroughly mix the added water to the minus No. 4 sieve material and store in an air-tight container for a minimum of 16 hr.

(4) The water content of the minus No. 4 sieve material after addition of water will then become:

$$W_{NO4WA} = \frac{WT_{WA} + P_{NO4}WT_{AD}W_{NO4}}{P_{NO4}WT_D}$$

16. Prepare material for four additional test specimens by repeating steps in 5a and 5b with the exception that the desired water content of the total specimen shall be increased approximately one percentage point for each succeeding specimen.

Compaction Procedure

17. The compaction procedure shall be as follows:

a. Clean the mold assembly and spray surfaces which will come into contact with soil with oil or other suitable lubricant. Wipe any excess lubricant from the surfaces. Check to see that the assembly base plate and the plate upon which it rests have sufficient grease or lubricant on them to insure ease of motion when rotating or moving the mold forward and backward.

b. Weigh the compaction mold to the nearest 0.1-lb.

c. Put together the mold assembly and place it in the compactor. Clamp the mold and mold collar to the assembly base plate.

d. Mix the cured minus No. 4 sieve material thoroughly and weigh out an amount of material obtained by the following equation:

$$WT_{bNO4} = \frac{P_{NO4}WT_D(1 + W_{NO4WA})}{3}$$

where

WT_{bNo4} = weight of cured minus No. 4 sieve material for a single layer

e. Mix the cured minus No. 4 sieve material for one layer with one of the previously prepared gravel batches for one layer. Place the combined material in the compaction mold. Each total layer batch thus prepared should contain slightly more than the required amount of material. The amount of combined material to use for a layer shall be based on testing experience.

f. Compact each of 3 layers of combined soil prepared as above using the appropriate procedure in the following table:

Procedure	Mold Diameter in.	Blows per Layer	No. of Coverages per Layer	Peripheral Blows per Coverage	Central Blows per Coverage
A	12	25	2	12[1]	0
B	18	83	5	12	5[2]

[1] plus 1 extra blow for last coverage
[2] minus 2 central blows for last coverage

g. To achieve approximately equal compacted layer heights and therefore, a compacted specimen extending approximately 1/4-in. into the mold collar, add or remove material from layer batches based on comparing desired and measured compacted layer heights. Compacted layer heights may be determined by subtracting the average of several measurements of the distance from the top of the mold collar to the surface of the compacted layer from the distance from the top of the mold collar to the mold base. Desired layer heights are 4.1 and 6.1-in. for the 12 and 18-in. diam molds, respectively. Amounts of material to add or remove are a matter of judgement based on testing experience.

h. After compacting the final layer, remove the extension collar from the mold. Remove compacted soil extending above the top of the mold with a knife and carefully trim the surface of the specimen even with the top of the mold using a straightedge. Large particles may be pounded flush with the top of the mold using a rubber headed maul. Smaller particles may be pulled out and resulting voids patched with material remaining from layer batches. When patching voids, material should be tamped or pushed into the voids to approximate the density of similar material in the specimen.

i. Remove the mold and specimen from the compactor and mold assembly. Brush excess material from the top of the mold and other locations on the mold where it may have accumulated. Weigh the mold plus wet specimen to the nearest 0.1-lb and record the weight on the test data sheet.

j. Remove the specimen from the mold and place the total specimen in pans for a water content determination. Soil from the specimen should be broken apart and spread in the pans to facilitate drying. Care should be taken to not loose any material during removal of the specimen from the mold and during placing and breaking down of the soil in the pans. For most specimens, the drying time is at least 16-hr. The first specimen of a test shall be left in the oven an additional day after a 16-hr weight is obtained to verify whether a 16-hr period is adequate.

k. Repeat steps a through j for the remaining specimens. Compact a sufficient number of test specimens over a range of water contents to establish the optimum water content and maximum unit weight. Do not reuse material. Generally, five compacted specimens obtained using the above procedure are sufficient to define a compaction curve. To determine if the optimum water content has been reached, compare the wet weights of the various compacted specimens. The optimum water content and maximum unit weight have been reached if the wettest specimens compacted indicate a decrease in weight in relation to drier specimens.

l. For tests in which degradation of particles due to impact of the rammer is significant, determine the gradation of at least two specimens after the final dry weight has been determined.

Computations

18. The following values are obtained for each test:

a. Weight of compaction mold plus wet soil. The weight of the compaction mold is subtracted from this value to obtain the weight of the wet soil, W.

b. The volume of the compaction mold. This volume is equal to the volume, V, of the soil specimen.

c. Weight of specimen plus pans. The total weight of the pans is subtracted from the total weight of the pans plus soil before and after drying to obtain a check of the weight of wet soil, W , and to obtain the dry weight of the specimen, W_s.

19. The water content of each specimen shall be calculated as follows:

$$w = \frac{W_w}{W_s} \times 100$$

where

w = water content of specimen expressed as a percentage

W_w = wet weight of total specimen, W, minus its oven-dry weight, W_s, i.e., the weight of water in the specimen

W_s = oven dry weight of specimen

20. The dry unit weight of each specimen shall be calculated as follows:

$$\gamma_d = \frac{W_s}{V}$$

Presentation of Results

21. The results of the compaction test for earth rock mixtures shall be presented as a compaction curve on an arithmetic plot. Dry unit weights shall be plotted as ordinates and the corresponding water contents as abscissas. The plotted points shall be connected with a smooth curve. Generally, the curve is parabolic in form. The water content corresponding to the peak of the compaction curve is the optimum water content and shall be recorded to the nearest 0.1 percent. The dry unit weight corresponding to the peak of the compaction curve is the maximum dry unit weight. The maximum dry unit weight shall be recorded to the nearest 0.1 pcf.

22. The zero air voids curve shall be included on the report sheet showing the compaction curve. The zero air voids curve represents the dry density and water content of a soil completely saturated with water. Data for plotting the zero air voids curve are given in Table VI-1 of EM 1110-2-1906. The specific gravity of the soil shall be the specific gravity based on the specific gravity of solids of the material passing the No. 4 sieve and the apparent specific gravity of the plus No. 4 sieve material. The method for calculating this value is give in Appendix IV of EM 1110-2-1906.

23. The gradation of the sample determined during processing of the soil shall be included with the report of test results along with any post test gradations.

Possible Errors

24. Possible errors in the test that can affect results are:

a. Aggregations of soil not completely broken down during processing.

b. Incomplete air drying of sample. Incomplete drying may result in nonuniform water content of stockpiled materials and produce errors in calculations for weights of material to reproduce the sample gradation.

c. Nonuniform water content of minus No. 4 sieve material batches due to insufficient mixing and/or curing time.

d. Reuse of minus No. 4 sieve material. Reuse of many clayey soils will increase the maximum dry unit weight and decrease the optimum water content.

e. *Insufficient range of water contents to define compaction* curve.

f. Hammer drop height not calibrated properly.

g. Excessive friction between guide bushings and hammer.

h. Excessive variation of layer heights

i. Improper foundation for mold during compaction.

j. Inaccurate balances or scales used to determine specimen weights.

k. Insufficient drying of specimen for determination of specimen dry weight.